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VON KARMAN CENTER

SNAP-8 DIVISION

SNAP-8 SEALS-TO-SPACE DEVELOPMENT TEST PROGRAM

VOL. II - MOLECULAR PUMP

A REPORT TO

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SNAP-8 SEALS-TO-SPACE DEVELOPMENT TEST PROGRAM

VOLUME II - MOLECULAR PUMP

By J. N. Hodgson

Contract No. NAS 5-417

a topical report to

NASA - LEWIS RESEARCH CENTER
SNAP-8 PROJECT OFFICE
H. O. SLCNE, SNAP-8 PROJECT MANAGER

Report No. 2808 (Topical) May 1964

AEROJET-GENERAL CORPORATION
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CONTRACT FULFILLMENT STATEMENT

This is Volume II of a four-volume topical report covering the SNAP-8 Seals-to-Space Development Test Program, and is submitted in partial fulfillment of NASA Contract No. NAS 5-417.

FOREWORD

The SNAP-8 seals-to-space concept involves the use of visco pump, molecular pump, and dynamic slinger elements. The seals-to-space program encompassed basic test work on each of these components for the purpose of demonstrating satisfactory performance for SNAP-8 operating conditions. In addition to the basic component tests, an overall integrated seal test rig was built and operated. This rig provided a nearly perfect simulation of the SNAP-8 turbine alternator assembly seal-to-space configuration and thermal environment, and demonstrated the satisfactory performance of the seal.

Volumes I through III of this report cover the work done on the visco pump, molecular pump, and dynamic slinger elements. Volume IV describes the design and operation of the integrated seal simulator.

The SNAP-8 Seals-to-Space Development Test Program was carried out under the auspices of the SNAP-8 Division, Von Karman Center, Aerojet-General Corporation, as part of the SNAP-8 Contract work.

Mr. C. G. Boone, Chief Engineer for the SNAP-8 Division, had overall responsibility for the SNAP-8 Seals-to-Space Development Test Program. Mr. R. L. Lessley, Engineering Department, SNAP-8 Division, had direct responsibility for the program. Assisting Mr. Lessley were E. A. Haglund, J. N. Hodgson, and I. L. Marburger, all of the Engineering Department, SNAP-8 Division.

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NOMENCLATURE

Symbol	Definition	Unit
a', a''	Flow equation constants	in.^{3}/sec
A	Area	in.^{2}
b	Channel width	in.
b', b''	Flow equation constants	in. lb/sec
B	Perimeter	in.
c_1, c_2, c_3, c_4	Flow equation constants	in.^{2}/lb
d	Flow - minimum correction factor	
D	Diameter	in.
f	Frictional force	lb
f_1, f_2	Coefficients of momentum transfer	
g	Gravitational constant, 386	in./sec^2
h	Channel depth	in.
k	Boltzmann Constant, 6.78×10^{-23}	in. lb/^{o}R
k_t	Momentum transfer time constant	
K_1, K_2, K_3	Geometrical factors	
ℓ	Coordinate along flow path	in.
L	Molecular pump length	in.
m	Mass of molecule	lb-sec^2/in.
N	Rotational speed	rpm
p	Pressure	lb/in.^{2}
p_o	Driving pressure	lb/in.^{2}
p_{e_o}	External pressure, at zero flow	lb/in.^{2}
Q	Volume flow rate at unit pressure	in. lb/sec

NOMENCLATURE (cont.)

Symbol	Definition	Unit
Q_N	Net volume flow rate at unit pressure	in. lb/sec
R	Gas constant	in./^oR
T	Absolute temperature	^oR
u_1, u_2	Molecular tangential velocities at boundary surfaces	in./sec
U	Rotor peripheral velocity	in./sec
$\bar{U}$	Average fluid velocity	in./sec
v	Velocity in direction of flow	in./sec
V	Volume flow rate	in.^{3}/sec
w	Land width	in.
W_N	Weight flow rate	lb/sec
y	Coordinate perpendicular to flow path	in.
α	Rotor-induced flow factor	in.^{3}/sec
β	Channel continuum flow factor	in.^{6}/lb-sec
γ	Channel molecular flow factor	in.^{4}/sec
η	Land continuum flow factor	in.^{6}/lb-sec
θ	Land molecular flow factor	in.^{4}/sec
δ	Radial clearance	in.
ϵ	Frictional force coefficient	lb-sec/in.^{3}
ζ	Coefficient of slip	in.
λ	Mean free path	in.
μ	Viscosity	lb-sec/in.^{2}
ρ	Density	lb/in.^{3}
ϕ	Helix angle	
Δ	Small increment	
$\bar{K}$	Constant relating mean free path and coefficient of slip	

SUMMARY

The seals-to-space of SNAP-8 require a means of restricting the flow of mercury and lubricant vapor out of the vent to space. This flow restriction is accomplished by use of a molecular pump - a highly effective form of flow restrictor based on the principle of the Holweck vacuum pump. Rather than using the static action of the conventional annulus or labyrinth, the molecular pump employs a dynamic action which moves molecules counter to the pressure gradient to space.

The theoretical performance of the molecular pump was derived in detail as part of the flow restrictor development program. The theory was developed based upon the assumption of purely molecular flow. A computer program was conducted which allowed optimization of the molecular pump dimensions over a large variety of operating conditions. The independent variables exercised were diameter, speed, temperature, length, clearance, and molecular weight.

A very basic problem exists, however, in that SNAP-8 operating conditions do not place the flow at the high-pressure end of the molecular pump in the molecular flow regime. On the contrary, the flow extends well into the continuum regime; thus the optimum configurations predicted by the optimization of the molecular theory are not truly optimum. To rectify this, a theory was developed which defines the performance of the molecular pump over the entire spectrum of flow regimes. This specially developed theory predicts the molecular pump performance for any given operating condition, and accounts for the changing flow regime within the pump itself. Unfortunately, the complexity of the final form of the performance equations has precluded an optimization program. However, sufficient insight into the flow phenomena has been gained by the theory to allow intelligent extrapolation from the molecular theory optimums toward the appropriate optimums for SNAP-8 operating conditions.

Several configurations were chosen for the test program. The first few configurations were optimum as predicted by the molecular flow theory. As the testing proceeded, the undesirable effects of the non-molecular flow conditions became apparent. Remedial measures were taken by increasing the number of threads/in. and tapering the groove depth to make it shallow at the high-pressure end of the molecular pump. Both procedures increased the ratio of mean free-path to channel dimensions, which served to make the flow more closely approach the molecular regime. The actual dimensions for these latter non-optimum configurations were based upon intuition and extrapolation from the molecular theory. Tests were conducted on both the optimum and non-optimum sets of configurations at temperatures of 300 and 375°F. The correlation between the theory and test data was good.

Three basic problems were encountered during the test program: (1) shaft seizure occurred several times during the initial phase of testing, (2) equipment malfunction caused interface temperatures to be well in excess of 400°F, and (3) entrained air in the bearing lubricant leaked into the molecular pump area causing pressure ratios to be low enough to lead to the premature conclusion

SUMMARY (cont.)

that the molecular pump was not functioning. Once these problems were brought under control, a successful test program was carried out. Both pressure ratio and leakage data are in good agreement with theoretical predictions.

The test program served to answer a number of questions regarding the effectiveness of the molecular pump as a flow restrictor. For example, it had not been known if the theory would adequately extend to the geometrical limitations of the SNAP-8 application. (SNAP-8 requires a short molecular pump and large radial clearance, whereas in the original context as a vacuum pump the molecular pump is long and depends heavily on the radial clearance being small.) The test program indicated that the theory extends well to the SNAP-8 requirements. It was not known what influence continuum flow effects might have on the performance of the molecular pump. As a result of the transition flow theory which has been developed, it is now possible to predict the influence of non-molecular flow conditions. Tests have been made substantiating the validity of the theory. It was not known what configuration should be recommended for SNAP-8. Before a specific configuration was selected, consideration was given to (1) the optimum values developed from the molecular flow theory, (2) transition flow theory, and (3) comparison of theoretical predictions with test results. The configuration selected has five threads/in., equal land and groove widths of 0.100 in., and a groove depth of 0.070 in.

I. INTRODUCTION

The turbine working fluid of the SNAP-8 system is mercury, whereas the bearing lubricant is oil. This situation creates a need for a seal-to-space inasmuch as the two fluids, somewhere in the system, occupy adjacent areas. Either the fluids are allowed to interdiffuse at their junction, the amount of which would be quite prohibitive, or they join to a common vent to space. The latter alternative can limit the interdiffusion of the fluids to negligible quantities and has been chosen as the design principle for SNAP-8.

With both oil and mercury having direct access to a vent to space, there necessarily must be a seal for each which allows only a minimum tolerable leakage. Since it is mandatory that the seals function for a minimum of 10,000 hours, no standard rubbing-contact seal can be used. It is evident that the seal-to-space must be a highly advanced, yet reliable component of the SNAP-8 system. This advanced seal design has been conceived, tested, and shown to be capable of fulfilling its requirements. The components of the seal-to-space are (a) a dynamic slinger (or alternatively, a visco-pump) to maintain a liquid-vapor interface, (b) a cooling system to control the liquid-vapor interface temperature within design tolerances, and (c) a flow restrictor to restrict the flow out of the space vent of molecules evaporating from the liquid at the interface. This report covers the third component of the seal-to-space, the flow restrictor. Although the test program is given primary consideration, theoretical design and interpretation are included as appropriate.

Prior to initiation of the SNAP-8 seal-to-space program at Aerojet-General Corporation, the standard method of restricting the flow of vapor along a shaft was by use of either a simple close-fitting annulus or a labyrinth. The leakage through an annulus or labyrinth was great enough to warrant research into new principles of vapor restriction. The molecular pump evolved as a result of this research. This type of flow restrictor is based on the principle of the Holweck molecular pump, a well-known type of vacuum pump commonly used in Europe some years ago (References 1 through 3). The pump is simple in principle, consisting of a rotating shaft surrounded by a helical channel (Figure 1). Molecules within the channel alternately strike the rotating shaft and stationary channel walls. As a result, they receive a net velocity in the direction of the channel, which in effect pumps them upstream and away from the vent to space. Since the pump outlet vents directly to space, there is a relatively large pressure gradient imposed upon the pump which induces a flow opposite in direction to the flow caused by the shaft motion. The overall effect is a small leakage out the space vent. The magnitude of this leakage to space is a function of the molecular pump configuration and the imposed operating conditions. The pump is capable of exceptional flow restriction and makes a very effective component for the SNAP-8 seal-to-space.

The theoretical performance of the molecular pump was derived in detail during the seal-to-space development program. The theory was developed first on the assumption of purely molecular flow conditions within the pump (Appendix A). Ideally, a molecular pump is not required to operate other than in the molecular flow regime. However, the conditions of SNAP-8 are out of the molecular flow regime, and well into the continuum flow regime. Consequently, it was necessary to develop an extended theory which defines the operation of a molecular pump under all conditions (Appendix B). A computer survey was made to determine the optimum geometrical configurations for a molecular pump as predicted by theory. Due to the complexity of the transition theory, it was deemed appropriate to base the computer study on the simpler molecular flow theory.

From the results of the computer program, test sections of optimum geometrical configurations were fabricated for the test program. The objectives of the test program were as follows: (a) to test the optimum configurations, (b), to make geometrical changes as found appropriate to better control the non-molecular flow conditions, and (c) to select a suitable molecular pump for use in the SNAP-8 seal-to-space. These objectives were successfully accomplished in the test program. The following pages outline the test program apparatus, methods, sequence of testing, and problems encountered. The test results are then summarized and interpreted in the light of theoretical considerations.

The insight from the flow restrictor program gives rise to some recommendations for interesting future research. First, the transition theory could profitably be analyzed on a computer to give optimum configurations for a few selected operating conditions. Future work on the transition theory might also include consideration of tapered groove depths and multi-flight threads. Although the number of thread flights appears to be of little consequence in molecular flow, it might be important in transition flow. Another innovation that appears rather promising is the use of grooves on both the rotor and stator. A preliminary analysis indicates that this would be beneficial. Another field of interest might be the construction of the molecular pump radially on a disk rather than axially. This has been done in vacuum pump applications (Reference 2). The construction need not necessarily be in the form of channels; a bladed-type molecular pump (Reference 4) which allows much greater clearances could conveniently be incorporated into a disk-type assembly. The extensions and improvements are numerous. The entire principle of flow restriction by means of the molecular pump is a promising field wortny of further investigation.

II. TEST APPARATUS, METHODS, AND PROBLEMS

A. APPARATUS

All tests were conducted in the Environmental Laboratory of the Astrionics Division, Von Karman Center. The laboratory is specifically designed for high-vacuum work and is therefore equipped with all the support equipment necessary for the molecular pump tests.

Figure 2 is an assembly drawing of the molecular pump test fixture. The basic functions of the fixture can be noted as follows:

1. Item A is the spindle, mounted on two sets of ball bearings. A sleeve at the test section region allows selection of any desired radial clearance. Clearances were varied from 0.001 to 0.005 in. during the test program. The spindle was driven at 12,000 rpm.

2. Item B is the molecular pump test piece. Numerous combinations of clearance, groove depth, threads/in., and materials were used during the program (see Sections III,A and III,B).

3. Item C is the vapor generator which supplies saturated mercury vapor to the region upstream of the molecular pump. Hence, it simulates the liquid-vapor interface of the SNAP-8 system. Temperature control is effected by a cartridge heater core and by temperature monitoring with thermocouples at the liquid pool surface (interface). The generator also contains a liquid-nitrogen passageway to freeze the mercury during the initial air evacuation phase of testing.

4. Item D is the space simulation component of the fixture. The entire region downstream of the molecular pump is connected, through valving, to a diffusion vacuum pump which provides for initial degassing of the system and subsequent space simulation.

5. Item E is the mercury condensate trap. This component is a removable cup which, during tests, is surrounded by a bath of liquid nitrogen. By weighing the trap before and after a test run, the condensate weight - and thus the leakage rate - can be determined.

6. Item F is the double-seal system to separate the bearing lubricant and the mercury vapor during tests. The region between the seals is maintained, by means of a second diffusion vacuum pump, at a pressure lower than the vapor generator pressure. This minimizes leakage of oil into the mercury side of the fixture.

7. Item G is the heating system for the test fixture itself. Hot nitrogen passes through passageways in the fixture to maintain the temperature above the vapor pressure of the mercury. Otherwise, condensation would occur at the test section rather than in the condensate trap.

Figure 3 shows schematically the lubrication system and instrumentation arrangements. Figure 4 is a photograph of the assembled and instrumented test fixture mounted between the two diffusion pump vacuum systems. The transparent plastic case is a safety feature to allow removal from the room of any mercury leaking from the fixture. A mercury vapor detector indicated no mercury leakage during any test.

B. METHODS

The method of conducting a test divides into seven basic parts as indicated on the following page.

1. Preliminary Degassing

Before any test, it is necessary to degas the entire mercury side of the system; this applies particularly to a newly assembled unit. Otherwise, it is impossible to get a good vacuum when the test is begun. If performed at an elevated temperature ($\approx 300^\circ F$), the degassing can be accomplished in 1 to 3 hours.

2. Mercury Freezing

The pool of mercury must be frozen during the initial phase of a test when the air is being evacuated from the system. Otherwise, the mercury would evaporate and be evacuated with the air.

3. System Evacuation

The diffusion pumps are next used to evacuate air and contaminants from the system. The length of time elapsing for this phase is partially determined by the completeness of the initial degassing process. The system is considered evacuated when the pressure level holds constant with no applied vacuum source. The interseal area should be maintained at a pressure below the evacuation pressure to minimize the leakage of oil and/or air into the mercury side of the system.

4. Start Rotation

This phase is preceded by a slight heating of the vapor generator to minimize any temperature-induced stresses. The lubricant flow is generally begun considerably before rotation to allow the lubricant flow rate and temperature to stabilize.

5. Temperature Control

The entire fixture is brought to the operating temperature. The housing temperature is maintained a few degrees above the generator temperature to eliminate condensation in the housing area.

6. Shutdown

Shutdown is effected by stopping rotation, bleeding air into the system, warming the condensate trap to room temperature, and shutting off all heat sources. Bleeding air into the system raises the pressure at the generator and halts the vapor leakage to the condensate trap. Cooling the generator to stop evaporation is also used, but is a relatively slow procedure.

7. Weight Recording

When the system has cooled sufficiently, the condensate trap is removed and weighed to determine the leakage rate.

C. PROBLEMS

Other than the usual minor problems involved in setting-up and instrumenting a test fixture and lubrication loop, there are three problem areas which affected either the progress or data of the test program. The problem areas are discussed below.

1. Shaft Seizure

During the first phases of testing, the program was beset with numerous cases of the shaft and test section rubbing and seizing. The possible explanations are numerous: vibration, misalignment, manufacturing and assembly errors, temperature-induced stresses, etc. Improvements, even complete correction, of many questionable areas and procedures were made. However, not until operation was limited to radial clearances greater than 0.003 in. was the problem completely eliminated. It appears that the problem may have stemmed from movements due to temperature gradients. The increased clearance completely eliminated the seizures and a successful test program was completed.

2. Interface Temperature

Erroneous interface temperature recording during the first phase of testing resulted in excessive temperatures which seriously impaired the apparent performance of the molecular pump. The interface temperature is recorded by thermocouples in the liquid mercury of the vapor generator. The vapor generator is a relatively complex component of the test fixture, having an internal liquid nitrogen passageway, two thermocouple leads which must be sealed vacuum tight, and a cartridge heater all combined into a small volume. Unfortunately, the only vapor generator available during much of the testing had thermocouples which were damaged either in the manufacture or in the delivery of the generator and which as a result were not operating.

In order to make some approximation of the interface temperature, other thermocouples were inserted as far as possible into the vapor generator housing thermocouple inlets, thereby allowing a measurement of the housing temperature relatively near the liquid mercury. Since it was known that the thermocouples would read low due to the insulating effect of the liquid nitrogen passageway and heat loss to the surroundings, it was assumed the actual interface temperature was 25 to 50°F above the thermocouple readings. Heating of the generator by the cartridge heater was restricted accordingly.

Finally, during the latter part of the test program, a new vapor generator was obtained that was equipped with functional thermocouples. It was found that the 25 to 50°F temperature difference assumed between the generator housing and liquid-vapor interface was much in error. By comparison of voltage settings previously used, it was found that all previous tests had been run with an actual interface temperature in excess of 400°F (rather than the assumed 300°F).

The vapor pressure of mercury at temperatures greater than 400°F is so high that the molecular pump could not possibly bring the flow into the molecular regime. Without being in the molecular regime, no pressure ratio of any consequence could be developed. The result was that all tests to that date showed very low pressure ratios and high leakage, leading to the premature conclusion that the molecular pump was not functioning well.

Future tests were most rewarding. The interface temperatures were held at the desired values, pressure ratios were good, and leakage values approached theoretical expectations. The highly successful latter phase of the test program, where the numerous data points were obtained, was initiated by this successful control of interface temperature.

3. Face Seal Leakage

The bearing lubricant and mercury vapor are separated by two face seals, the area between which is connected to a high-vacuum system. The purpose of this seal system is to draw off any mercury and oil which leak through their respective seals. In general, the seals were unable to maintain good sealing at 12,000 rpm. Wear rates were very acceptable, but the ability to seal against a vapor (or even a liquid) was poor with rotation. This condition held regardless of the care taken in initial alignment and surface honing of the seals.

On a few occasions, tests were ended ahead of schedule due to excessive oil leakage. This, though, was only a minor problem. The prime problem associated with the imperfect sealing was the effect produced on pressure ratio data. The lubricating oil had a certain amount of entrained air. The increased temperature at the seal area assisted in the release of this air which then migrated through the oil seal to the interseal area and, subsequently, through the mercury seal into the molecular pump area. Although mercury molecules were flowing in the opposite direction through the mercury seal, with the flow in the molecular regime they essentially do not hinder the air molecule flow. The flow of air molecules continues until an equilibrium pressure builds up in the molecular pump area.

The effect on pressure ratio data lies in the fact that air, consisting as it does of relatively light molecules, is not pumped so well as is mercury by the molecular pump. Consequently, air molecules rather readily pass through the molecular pump to the downstream area until they build up a pressure downstream dictated by the molecular pump's particular ability to pump air molecules.

The above phenomenon is readily observed in the pressure ratio data of the test program. Frequently, a substantial pressure ratio, characteristic of mercury vapor, would persist for considerable periods of time (30 or 40 min) until the seals began to leak. As the interseal area pressure began to rise, indicating an increased seal leakage, the pressure ratio would begin to drop. This drop would continue until an equilibrium pressure ratio characteristic of air molecules developed. It was possible to temporarily evacuate the air that occupied the molecular pump area by opening the valve to the diffusion pump connected to the downstream area. However, once seal leakage had begun, this relief was only temporary, and a very rapid return to the air pressure ratio occurred. The opening and closing of the downstream vacuum valve is represented by the discontinuities in the pressure-ratio data curves.

Although the air leakage greatly affected the pressure-ratio data, the effect on leakage data can be disregarded. The pressure of mercury vapor at the molecular pump entrance is determined solely by the interface temperature. The presence of air molecules increases the total pressure but has no effect on the mercury-vapor driving pressure. The air molecules develop a partial-pressure ratio which is small, whereas the mercury molecules develop a partial-pressure ratio which is large. The recorded pressure ratio is therefore small, but the mercury leakage goes on independently at the rate dictated by the higher pressure ratio. Subsequent to this program, tests on the SNAP-8 Seal Simulator were conducted both with and without the presence of air molecules. These tests showed no measurable effect of the air molecules on leakage rate.

III. TEST RESULTS

In this section, the entire testing sequence is outlined. Each molecular pump configuration is described and a brief summary of pertinent happenings is given. All test sections have a diameter of 1.625 in., a length of 2.00 in., and a single flight thread. All tests were made at a speed of 12,000 rpm. The test sequence below is divided into Parts I and II. Part I represents the testing period during which seizures occurred and during which excessive interface temperatures were being used. In spite of these difficulties, some meaningful leakage data were obtained which were in keeping with expected values for the higher temperatures.

Part II contains the testing sequence for the latter phase of the program. During this phase, the radial clearance was increased to 0.0043 in. and the temperature at the interface was accurately controlled. The testing was a complete success. Data were obtained at temperatures of 300 and 375°F, and a good correlation with theory resulted.

Section III,C presents an interpretation of the test results. The data points are explained in light of the theoretical predictions. Both the molecular regime and transition regime are included.

A. PART I OF TEST SERIES

Listed below are the principal features of each configuration tested, and the basic results of the tests.

1. Configuration 1

Configuration 1 consisted of a stainless-steel molecular pump (Figure 5) with groove dimensions optimum for 0.002 in. radial clearance. The actual radial clearance was 0.0018 in. The groove width was 0.180 in., and the land width was 0.150 in. (3.03 threads/in.). The groove depth was constant at 0.070 in.

This configuration operated for about 30 min; then the shaft and test section seized. Excessive vibration of the entire fixture was noted.

The vibration was later found to be the result of a manufacturing error; the drive spline was about 0.012 in. eccentric. Low pressure ratios were recorded as a result of the excessive interface temperatures. No leakage value was taken since the startup and shutdown procedures had allowed considerable opportunity for mercury leakage during periods of no rotation.

2. Configuration 2

Configuration 2 consisted of a stainless-steel molecular pump (Figure 5) with groove dimensions optimum for 0.002 in. radial clearance. The actual radial clearance was 0.004 in. The groove width was 0.180 in., and the land width was 0.150 in. (3.03 threads/in.). The groove depth was constant at 0.070 in.

This configuration was the same one used in paragraph III,A,1 with the exception that burrs and other surface irregularities from the seizure had been removed. Damage was more severe at one end and, consequently, the clearance was not constant. An average clearance is assumed of approximately 0.004 in. Excessive vibration due to the spline eccentricity again occurred. Pressure ratios again were low due to temperature effects. The fixture ran for 1.5 hours at which time shutdown was initiated due to excessive oil seal leakage. The mercury leakage rate was 15 lb/10^4 hours.

3. Configuration 3

Configuration 3 consisted of a stainless-steel molecular pump (Figure 6) with groove dimensions optimum for 0.003 in. radial clearance. The actual radial clearance was 0.0032 in. The groove width was 0.250 in., and the land width was 0.213 in. (2.16 threads/in.). The groove depth was constant at 0.071 in.

The vibration problem was corrected by switching to a shaft with a concentric spline. Low pressure ratios were again developed due to temperature effects. The fixture ran for about 30 min at which time the shaft and test section seized. The mercury leakage rate was approximately 6 lb/10^4 hours.

4. Configuration 4

Configuration 4 consisted of a carbon molecular pump (Figure 7) with radial clearance of 0.0015 in. The groove width was 0.130 in. and the land width was 0.120 in. (4.00 threads/in.). The groove depth tapered from 0.005 to 0.050 in.

The approach was taken of using a carbon test section and allowing it to wear-in at low speed prior to the actual test run. After a careful slow speed run-in period the mercury test was begun. The test lasted about 30 min at which time the shaft and carbon seized. Considerable damage to the sleeve had resulted. No leakage data were taken. This marked the first test using a tapered groove for greater ability to handle the transition regime flow.

5. Configuration 5

Configuration 5 consisted of a Teflon molecular pump with a radial clearance of 0.003 in. The groove width was 0.110 in. and the land width was 0.090 in. (5.00 threads/in.). The basic section was 1.40 in. in length and had a constant groove depth of 0.045 in. A pre-molecular-pump section had a length of 0.50 in. and a constant groove depth of 0.006 in.

This configuration was fabricated of Teflon in an attempt to provide a wear-in ability should the shaft and test section touch. An innovation was the use of a pre-molecular pump section to handle the transition regime flow. The pre-molecular pump was simply a short length of molecular pump, the groove depth of which was very shallow. The depth of groove was made optimum for continuum regime flow. This configuration was the first to show acceptable pressure ratio data. The test was run at a reduced temperature as a safeguard for the Teflon and hence removed the temperature effect which had previously been hindering the development of ample pressure ratios. The test was discontinued after about 35 min when the pressure ratio was suddenly lost. The Teflon and shaft had seized, but rotation continued due to the low strength of Teflon. Powdered Teflon coated the entire inside of the fixture up to the mercury face seal. No leakage data were obtained.

6. Configuration 6

Configuration 6 consisted of a stainless-steel molecular pump (Figure 8) with groove dimensions optimum for 0.001 in. radial clearance. The actual radial clearance was 0.002 in. The groove width was 0.120 in., and the land width was 0.091 in. (4.74 threads/in.). The groove depth was constant at 0.058 in.

This test was characterized by extreme care in assembly and alignment to minimize the possibility of a seizure. Seizure occurred almost immediately, within about 3 to 4 sec of startup. At this point it was decided to conduct an extensive examination of shaft perturbations, temperature-induced motions, alignment problems, etc.

7. Configuration 7

Configuration 7 consisted of a stainless-steel molecular pump (Figure 9) with a radial clearance of 0.003 in. The groove width was 0.110 in., and the land width was 0.090 in. (5.00 threads/in.). The groove depth tapered from 0.015 to 0.080 in.

This and all future test sections are marked by a modified test section which places the molecular pump about 1-1/2 in. closer to the bearings. This was done to minimize the magnitude of shaft perturbations at the test section. The shaft seized after about 14 min of operation. However, good pressure ratio data were obtained. No leakage measurement was made since there was no discernible amount.

8. Configuration 8

Configuration 8 consisted of a stainless-steel molecular pump (Figure 9) with a radial clearance of 0.0043 in. The groove width was 0.110 in., and the land width was 0.090 in. (5.00 threads/in.). The groove depth tapered from 0.015 to 0.080 in.

From this point on, no tests were run with radial clearances less than 0.004 in., and no further seizures occurred. The test was continued for 3 hours with a measured leakage rate of 1.6 lb/10^4 hours. This low leakage value is the result of using cooling in the face seal area which lowered the effective interface temperature even below 300°F.

9. Configuration 9

Configuration 9 consisted of a stainless-steel molecular pump (Figure 10) with a radial clearance of 0.0043 in. The groove width was 0.110 in., and the land width was 0.090 in. (5.00 threads/in.). The basic section was 1.40 in. in length and had a constant groove depth of 0.070 in. A pre-molecular-pump section had a length of 0.50 in. and a constant groove depth of 0.014 in.

The fixture was operated for 3 hours and gave a leakage rate of about 30 lb/10^4 hours.

B. PART II OF TEST SERIES

The demarcation between Part I and Part II of the test program was the acquisition of a vapor generator with functional thermocouples. It became apparent that previous tests had been run with interface temperatures well in excess of 400°F; hence the poor pressure ratios and high leakage rates. The ability to accurately control interface temperature, together with the decision to run at radial clearances of 0.004 in. or greater, indicated that an eminently successful series of tests would follow. Such was the case. Four configurations of molecular pump were fabricated which investigated the effects of both a tapered groove depth and the number of threads per unit length. All but one configuration were run at both 300°F and 375°F so as to investigate the effects of shifting well into the continuum flow regime. Pressure ratio data and leakage rates were measured on each test. Since all the tests were conducted identically and require no individual description, they are summarized in Table 1. Section III,C is devoted to an interpretation of the Part II Test Series results and conclusions as they relate to the SNAP-8 system.

C. INTERPRETATION OF PART II TEST RESULTS

1. Leakage Data

All the leakage test results of Part II are included as Figures 13 through 16 where each molecular pump configuration is represented on a plot of leakage rate vs temperature. To give a meaningful comparison, each plot also includes leakage values for an annulus and the theoretical predictions for the

TABLE 1

SUMMARY OF PART II TEST SERIES

Photograph	Clearance (in.)	Threads/in.	Groove Depth (in.)	Groove Width (in.)	Land Width (in.)	Temp (°F)	Run Time (hours)	Leakage Rate (lb/10^4 hours)
Figure 11	0.0043	5	0.070	0.110	0.090	300	2.8	1.2
						375	2.8	30
Figure 9	0.0043	5	0.015-0.080	0.110	0.090	300	1.3	3.2
						375	1.0	8.8
--	0.0043	2	0.015-0.080	0.280	0.220	300	2.0	1.4
						375	1.0	22
Figure 12	0.0043	2	0.080	0.280	0.220	300	2.3	2.4

molecular pump based on both the molecular theory and the transition theory. Appendix A presents the mathematical basis for the molecular flow curves, and Appendix B gives the basis for the transition flow curves. To present both the molecular and transition theory considerations, the interpretation of the test results which follows is divided into two categories: (a) a comparison of the test data with the molecular flow theory, and (b) a comparison of test data with the transition theory.

a. Comparison with Molecular Flow Theory

The mean free path of saturated mercury vapor is such that the molecular flow regime is being taxed at 300°F; at 375°F the flow definitely favors the continuum regime. Accordingly, the agreement between test data and the molecular flow theory should be relatively good at 300°F, whereas at 375°F there should be evidenced a substantial deviation between theory and test. This general trend is well exemplified in Figures 13 through 16.

There are two basic approaches available to increase the ability of a molecular pump to handle transition regime flow conditions. One method is to increase the number of threads per unit length; the other is to taper the groove to a very shallow depth at the pump entrance. Both methods decrease the basic distance a molecule must travel before another collision with a surface of the molecular pump. Whether one or a combination of both these methods is best is a function of the operating conditions. At present, there is no theory developed which allows optimization with a variable groove depth. The pressure ratio and leakage equations of the transition theory are sufficiently complex that making the groove depth a function of pump length was deemed a prohibitive complication.

At 300°F there is good agreement between theory and test results for the configurations of Figures 13 and 14. This is attributed to the fact that the configuration of Figure 13 has many threads per unit length, and the configuration of Figure 14 has both many threads per unit length and a tapered groove depth. When a decrease is made in the number of threads per unit length, as in the configuration of Figure 15, the leakage begins to exceed the theoretical value. In the configuration of Figure 16, neither the many threads per unit length nor the tapered groove depth is used. As would be expected, the flow departs even further from the molecular regime, and the leakage is far above theoretical predictions.

At 300°F the best of the four configurations is represented by Figure 13, which has 5 threads/in. However, assuming purely molecular flow, the theory specifies that 2 threads/in. is optimum. No tests were conducted at a lower temperature to test this relationship between 5 and 2 threads/in. Regardless of this, the trend to favor only 2 threads/in. is observed even with the relatively stringent conditions at 300°F. With respect to the configurations of Figures 14 and 15, the 2 threads/in. test showed much less leakage than the 5 threads/in. test. The tapered groove depth of the two configurations apparently gave enough control to the transition flow effects that the optimum nature of only 2 threads/in. could manifest itself. It is presumed that, at a lower temperature, the 2 threads/in. configuration would show up the more favorable even without the tapered groove depth.

Operation at 375°F shows some further interesting results. The higher temperature operation should increase the discrepancy between the test data and the molecular flow theory. This, of course, occurred as can be seen for the configurations of Figures 13 through 15. (The configuration of Figure 16 was not tested at 375°F because it would obviously have a very high leakage rate.) The configuration of Figure 14 is of interest. This configuration has both an increased number of threads per unit length and a tapered groove depth. Therefore, this configuration should have a reasonable ability to handle the transition conditions at 375°F. This ability is best observed in Figure 17 which is a plot of the experimental data only. The tapered, 5 thread/in. configuration leakage curve has the least slope of any in going from 300 to 375°F. The very low leakage at 375°F is questionable and perhaps represents an experimental error. However, the transition theory confirms the low slope of the leakage curve for this configuration. It can be concluded that increasing the threads per unit length and introducing a tapered groove depth increases the ability to handle transition regime flow.

It is to be remembered that the optimization studies done for the molecular pump are only for molecular flow. The choices of 5 threads/in. and the particular tapers used on grooves were selected by intuition and are necessarily somewhat arbitrary. Thus, the best configurations, chosen on the basis of the test results, are not necessarily optimum. However, as compared to the plain annulus the advantage of the test pieces selected is pronounced.

b. Comparison with Transition Flow Theory

Appendix B presents the development of a molecular pump theory which is applicable over the entire range from continuum flow to molecular flow, including the transition within the pump itself. Time and the expense of the computer program which would be required precluded an optimization of the resulting pressure ratio and leakage equations. However, even though it is not possible to find the optimum configuration, it is at least possible to evaluate the performance of a given configuration. This is possible since the pressure ratio equation lends well to a trial and error solution. By trial and error each configuration of the test program was analyzed to determine its pressure ratio at 300 and 375°F. By then making the sufficiently accurate assumption that leakage rate is inversely proportional to pressure ratio, the leakage rates were evaluated for each configuration. These leakage data form the curves of the transition theory in Figures 13 through 16.

The transition theory is observed to be a considerable improvement over the molecular theory. This improvement is particularly marked at 375°F but is also evident at 300°F. At 300°F, the molecular and transition theories are in close agreement in Figures 13 and 14 which represent the 5 threads/in. constant groove depth and tapered groove depth configurations, respectively.

This is as would be expected since 5 threads/in. gives small enough channel dimensions that the molecular theory is not far from accurate. Proceeding to Figures 15 and 16, which describe the 2 threads/in. tapered and constant groove depths, respectively, the advantage of the transition theory becomes most apparent. The constant groove depth is the best example. Since 2 threads/in. with a constant groove depth takes the flow well out of molecular flow, the recorded leakage value is a decade above the molecular theory value. The transition theory, however, brings good agreement between theory and experiment. The tapered groove depth likewise shows improvement with the transition theory.

The leakage rates measured at 375°F are lower than predicted by the transition theory. The reasons for this are not fully understood. However, it is possibly due to an increased flow upstream in the molecular pump due to the inability of the cold trap collection system to fully simulate space at the higher leakage rates characteristic of the elevated temperature. The increased upstream flow lowers the net leakage. It is quite reasonable to expect the high leakage rates at 375°F as given by the transition theory, for the mean free path at this temperature is well below 0.001 in. This means that channel dimensions are as much as 100 times the mean free path.

The limits of the transition theory for very low and very high temperatures are evident in the leakage plots. As the temperature decreases, the transition theory approaches the molecular theory asymptotically. At the other extreme, the transition theory intercepts and exceeds the leakage rate for an annulus. This latter phenomenon is to be expected since the optimum groove depth in continuum flow is much less than that for molecular flow. Therefore, the channel becomes a considerable leakage path in continuum flow and the leakage exceeds that for an annulus.

It appears that the test data are reasonably well coordinated with theory. By optimizing the transition flow equations, optimum channel dimensions could be known for any operating temperature. At present, however, the theory based on molecular flow, together with good judgment, must suffice for design purposes.

2. Pressure Ratio Data

As discussed in Section II,C,3, the pressure ratios registered during much of the testing were adversely affected by the presence of air molecules. However, enough testing was accomplished where the air problem was not excessive to allow a meaningful analysis of the pressure ratio capability of molecular pumps. The pressure ratio data are plotted as Figures 18 through 23.

The molecular pump configuration selected for SNAP-8 has 5 threads/in. and a constant groove depth. The performance of this configuration is presented in Figures 18 and 19. Figure 18 shows the pressure ratio data for air, taken before mercury was added to the system. The agreement with theory is good. The hump observed in the curve is rather common to the tests. It is the result of start transients. Since the upstream volume is small compared to the downstream volume, pressure transients upstream are not immediately reflected downstream, and the pressure ratio is affected accordingly.

Figure 19 shows the mercury pressure ratio data of the SNAP-8 configuration. Again excellent agreement with theory is observed. The excellent agreement lasts for about 1-1/2 hours at which time the pressure ratio takes a sudden decrease and, as can be observed, approaches the value characteristic of air. The sudden decrease is associated with face seal leakage which allowed air from the oil lubricant through to the mercury side of the test fixture. When the pressure ratio was lost, the downstream volume was next briefly evacuated of air by opening and closing the valve to the vacuum system. This process allows the beginning of a new pressure ratio transient as represented by the second curve of the figure. However, once seal leakage begins it is permanent, and the pressure ratio very rapidly again seeks equilibrium at, or near, the value for air.

Figures 20 through 23 show pressure ratio data for other combinations of configuration and temperature. Most equilibrium pressure ratio values in these figures are characteristic of air or a compromise between air and mercury indicating a degree of air leakage into the system.

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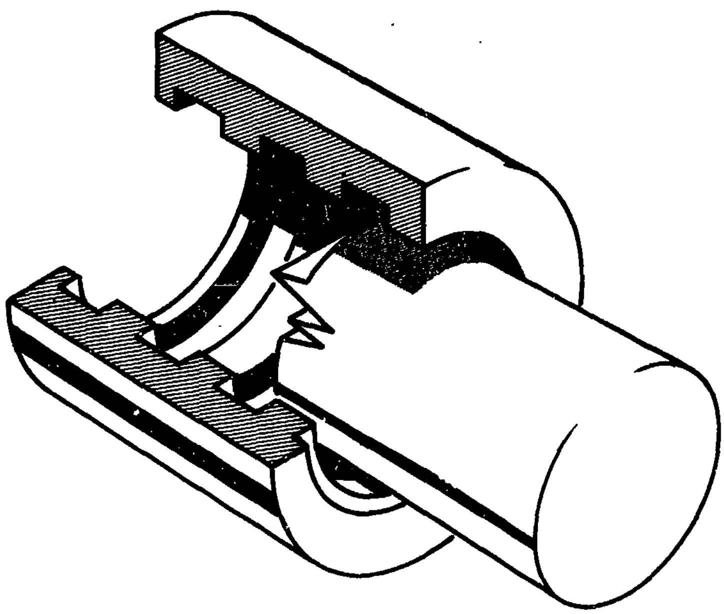
4. C. H. Kruger and A. H. Shapiro, "Rarefied Gas Dynamics," Proceedings of the Second International Symposi-m on Rarefied Gas Dynamics, University of California, Berkeley, 1960 (Supplement No. 1, Academic Press, 1961).



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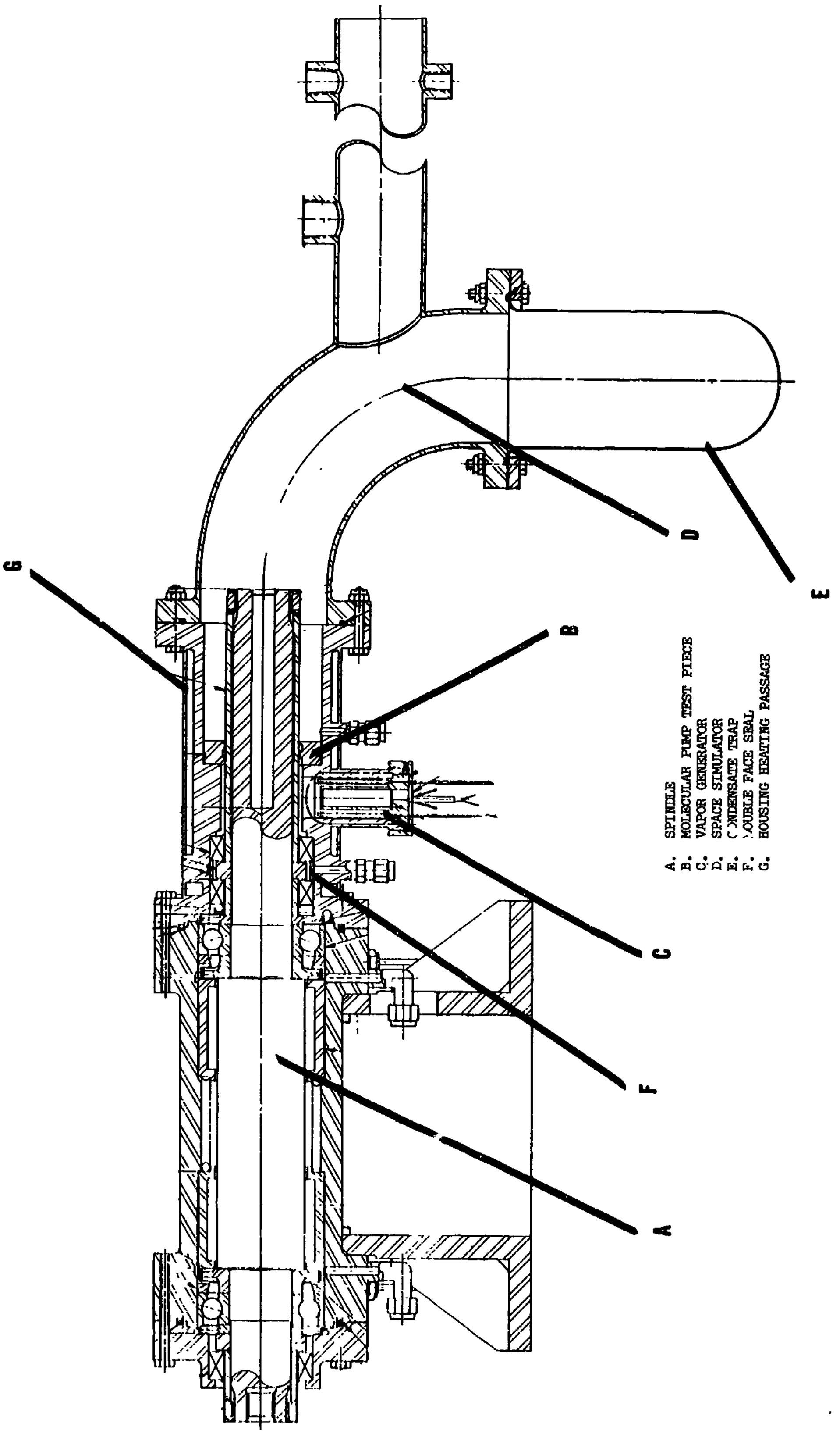
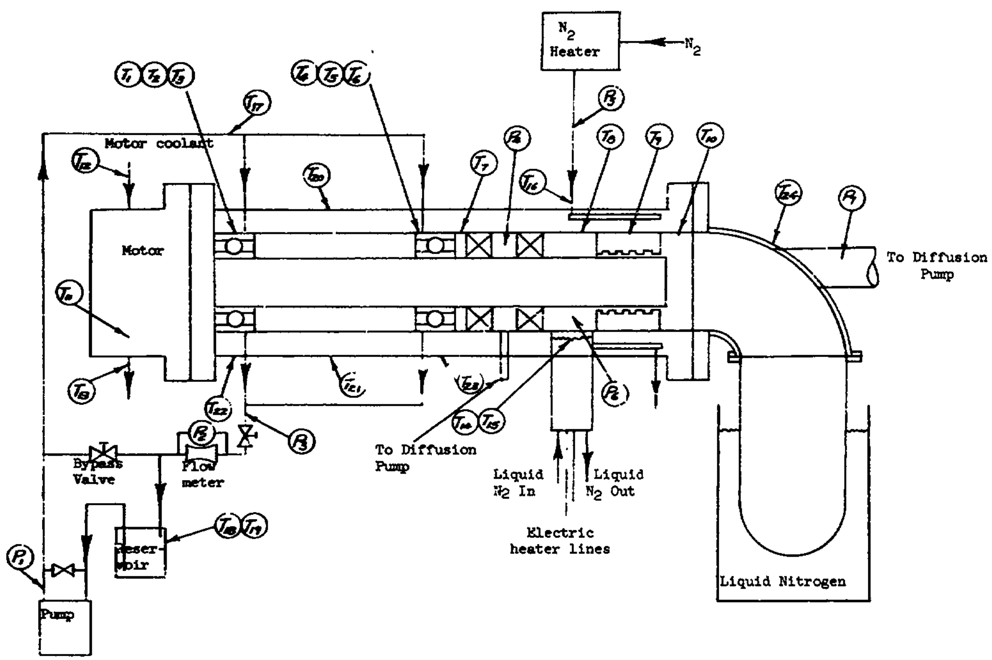
Molecular Pump Channel Configuration

Figure 1



Molecular Pump Test Fixture - Major Components

Figure 2



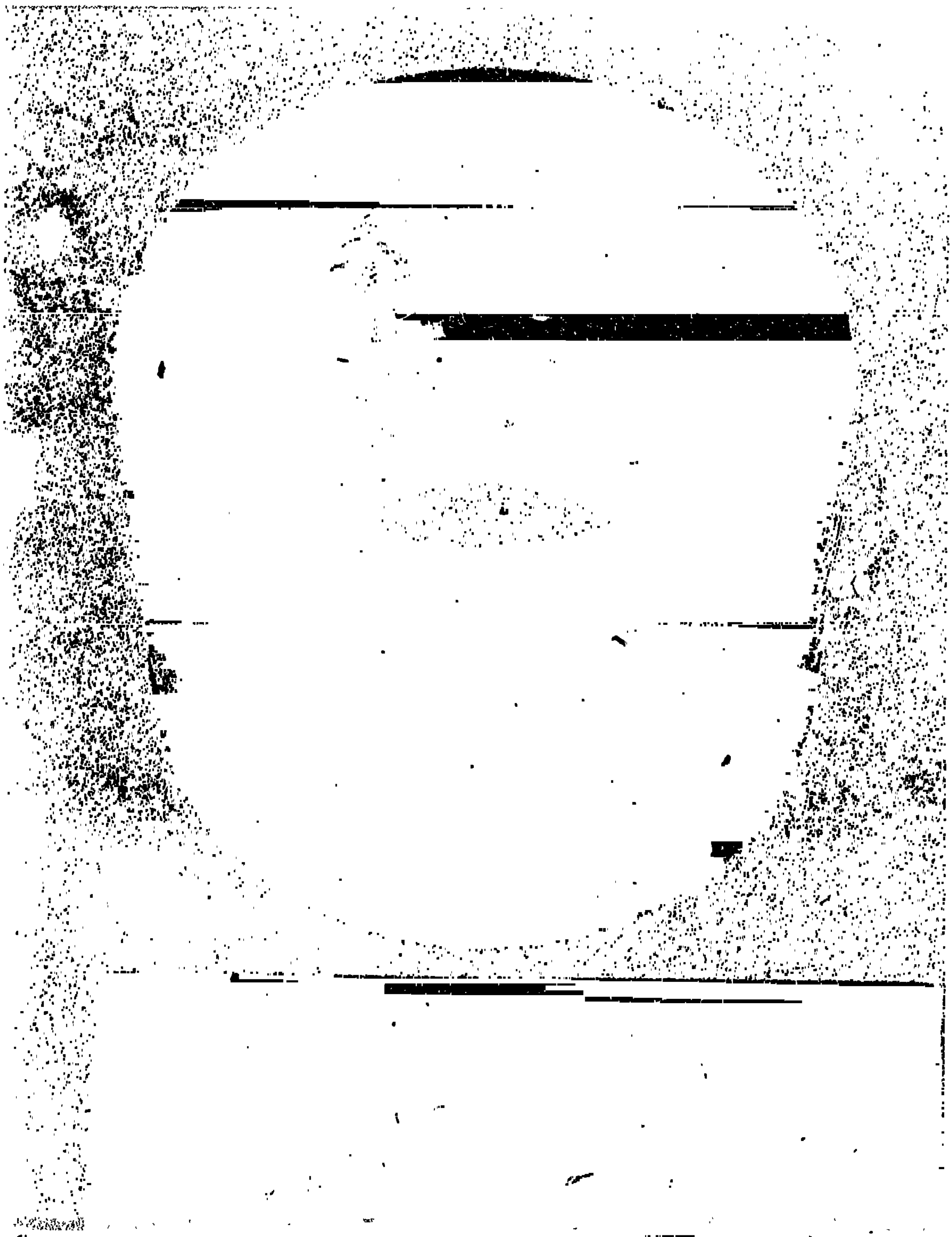
TEMPERATURE	STATION
T_1	Bearing - motor end
T_2	Bearing - motor end
T_3	Bearing - motor end
T_4	Bearing - test section end
T_5	Bearing - test section end
T_6	Bearing - test section end
T_7	Between seal and bearing
T_8	Entrance to test section
T_9	Center of test section
T_{10}	Downstream of test section
T_{11}	Motor case
T_{12}	Motor coolant inlet
T_{13}	Motor coolant outlet
T_{14}	Liquid-vapor interface
T_{15}	Liquid-vapor interface
T_{16}	N_2 - inlet to heating jacket
T_{17}	Oil - inlet to bearing
T_{18}	Oil - reservoir case
T_{19}	Oil - reservoir case
T_{20}	Housing - top center between bearings
T_{21}	Housing - bottom center between bearings
T_{22}	Housing - motor end at bearing
T_{23}	Housing - test section end at bearing
T_{24}	Housing - elbow to cold trap
PRESSURE	**STATION**
P_1	Pump outlet
P_2	Flow meter Δ P
P_3	Bearing outlet
P_4	Seal cavity
P_5	N_2 heater
P_6	Hg vapor pressure at generator
P_7	Molecular pump exit pressure

Molecular Pump Test Fixture - Instrumentation and Support Systems

Figure 3

Photograph of Molecular Pump Test Fixture

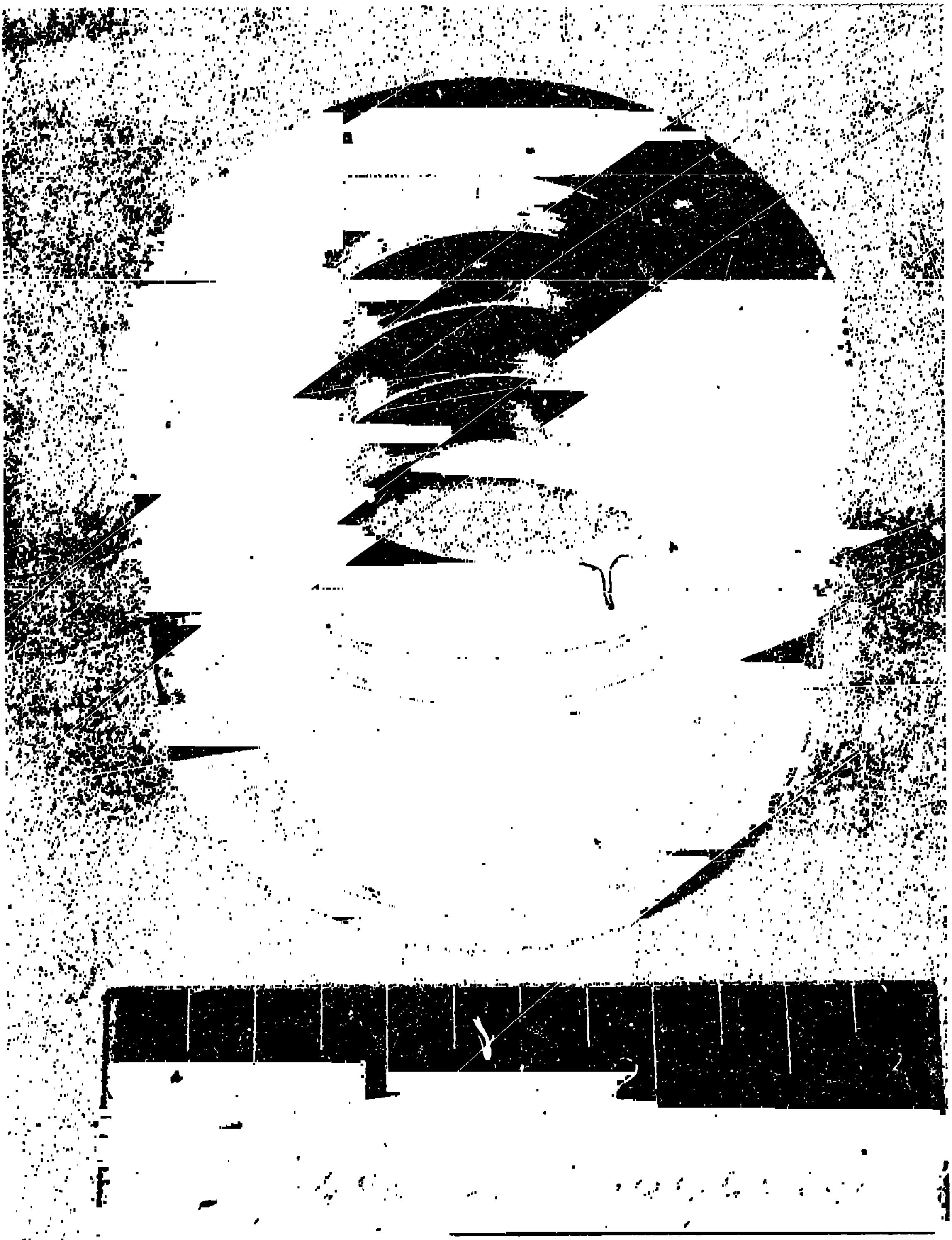
Figure 4



164-939

Test Section - Optimum Configuration for 0.002 in.
Radial Clearance (Constant Groove Depth = 0.070 in.;
Groove Width = 0.180 in.; Land Width = 0.150 in.)

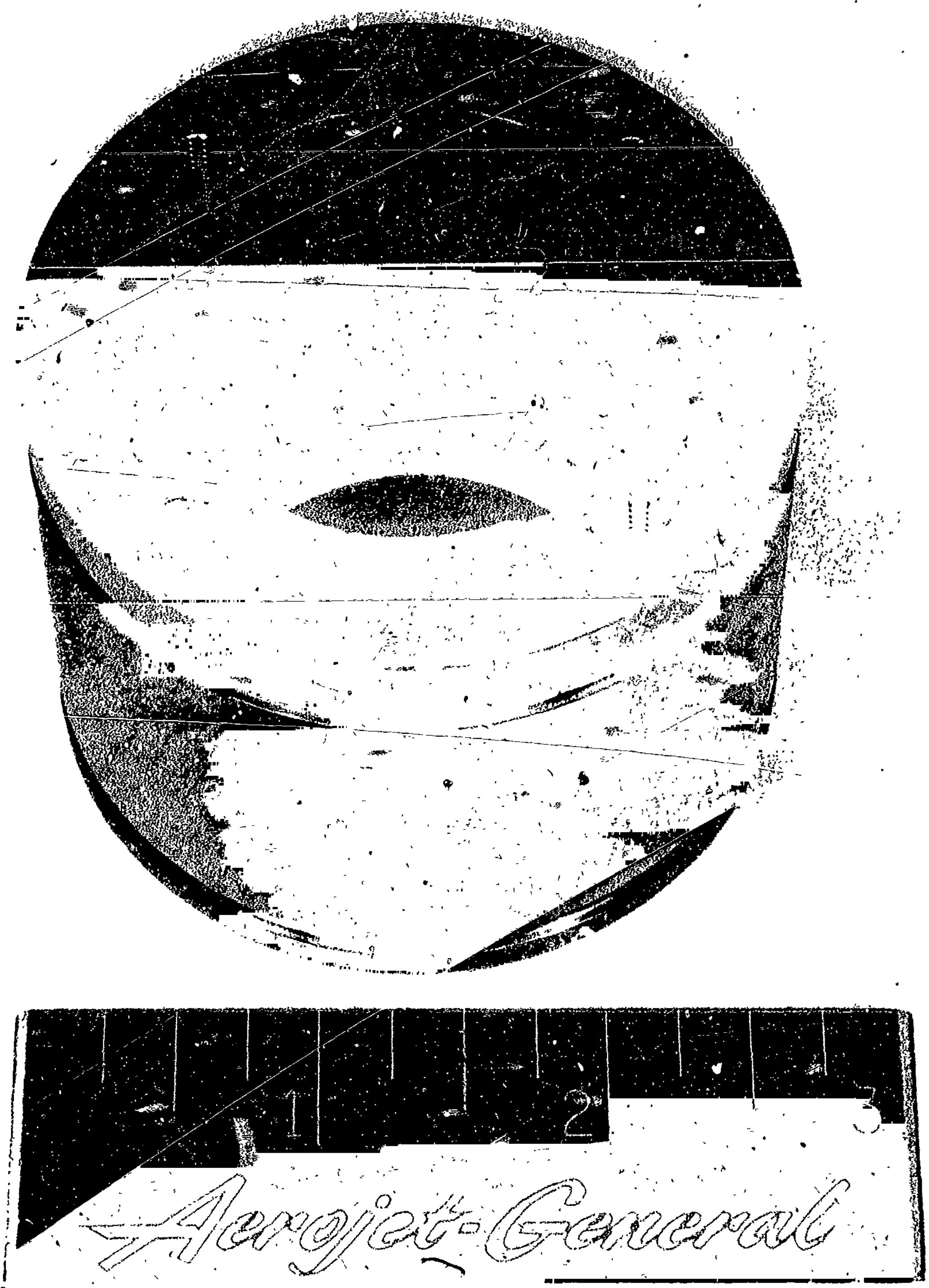
Figure 5



164-940

Test Section - Optimum Configuration for 0.003 in. Radial Clearance (Constant Groove Depth = 0.071 in.; Groove Width = 0.250 in.; Land Width = 0.213 in.)

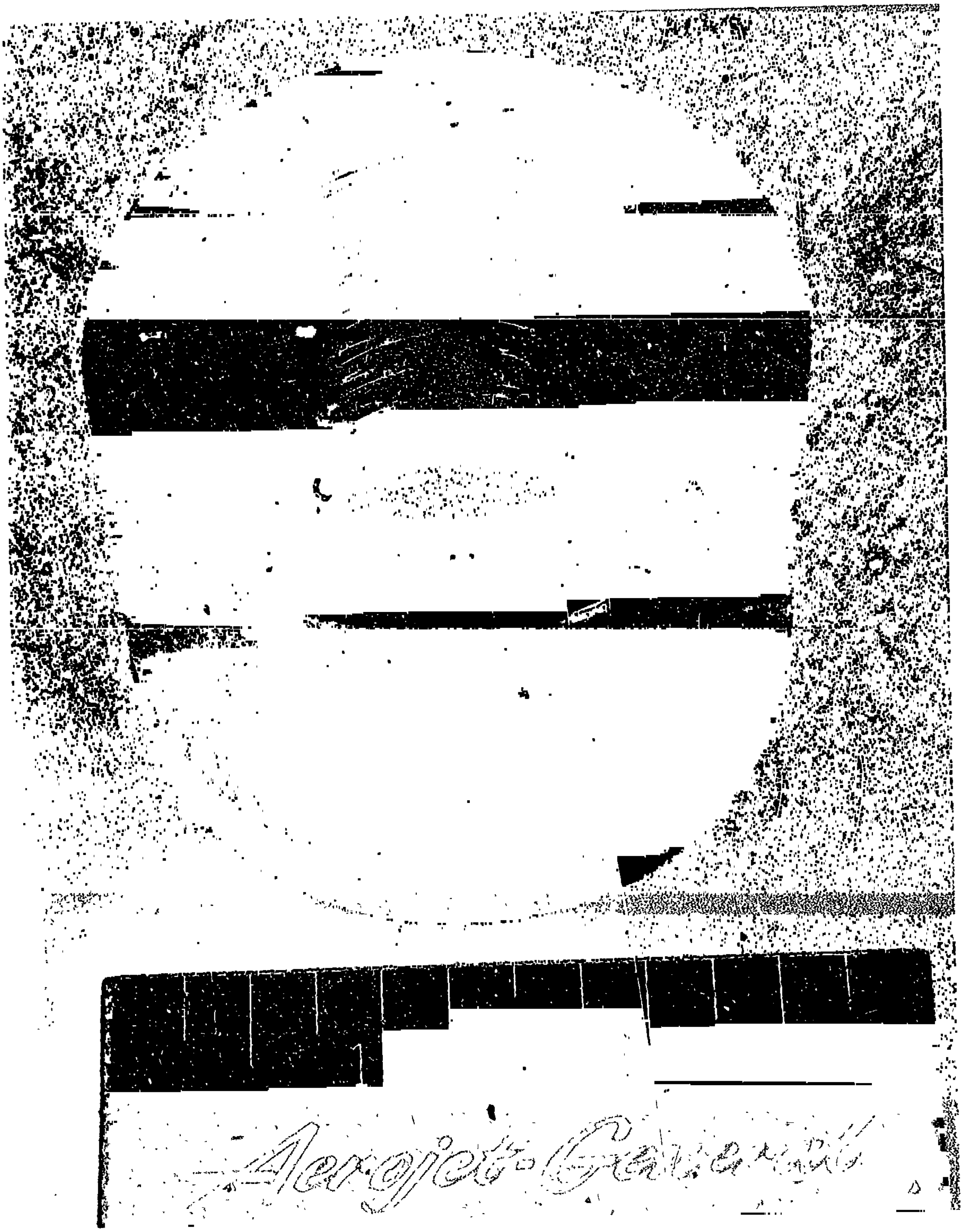
Figure 6



164-941

Test Section - Carbon Insert (4 Threads/in.;
Tapered Groove Depth = 0.005-0.050 in.;
Groove Width = 0.130 in.; Land Width = 0.120 in.)

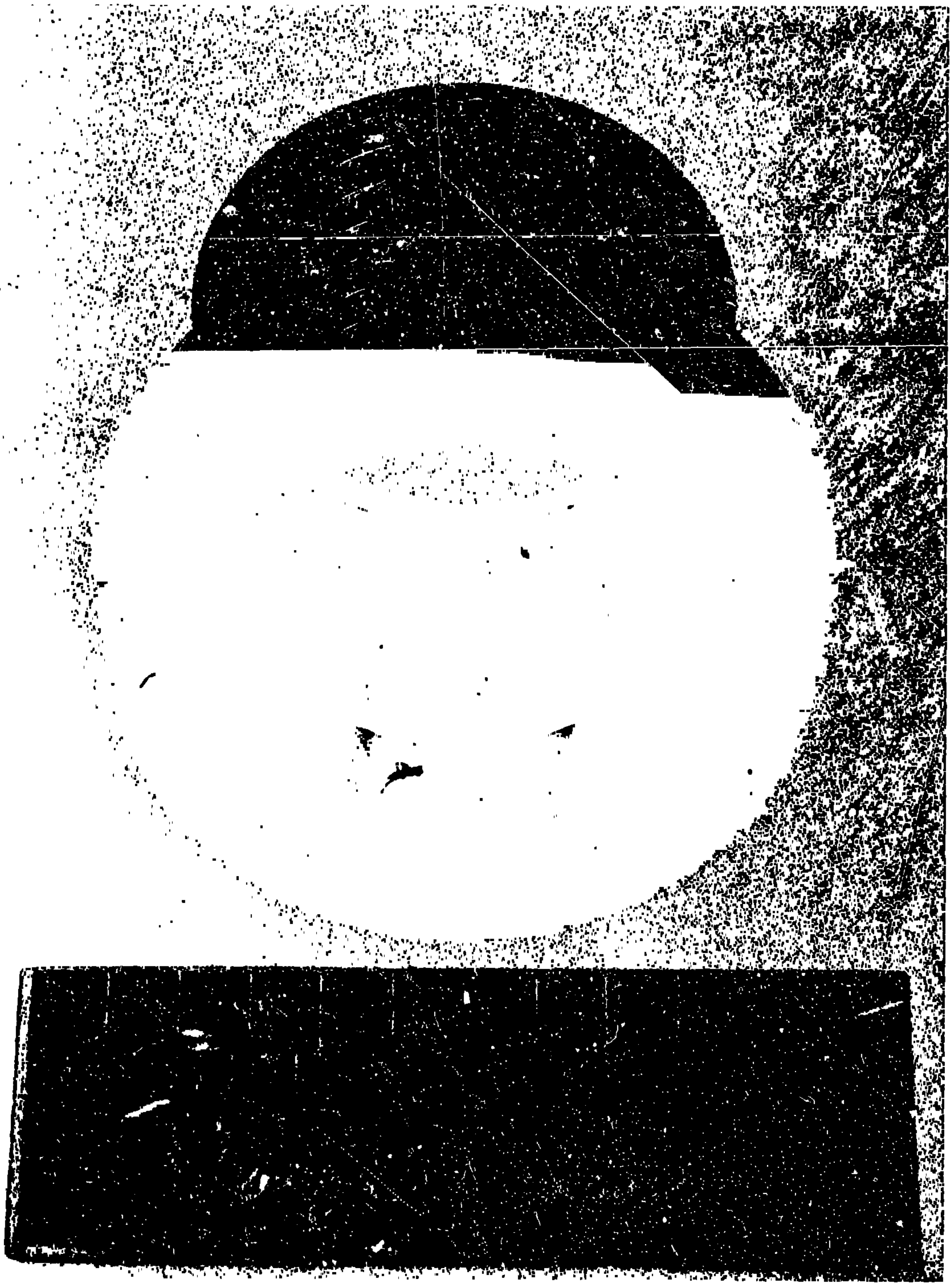
Figure 7



164-942

Test Section - Optimum Configuration for 0.001 in. Radial Clearance (Constant Groove Depth = 0.058 in.; Groove Width = 0.120 in.; Land Width = 0.091 in.)

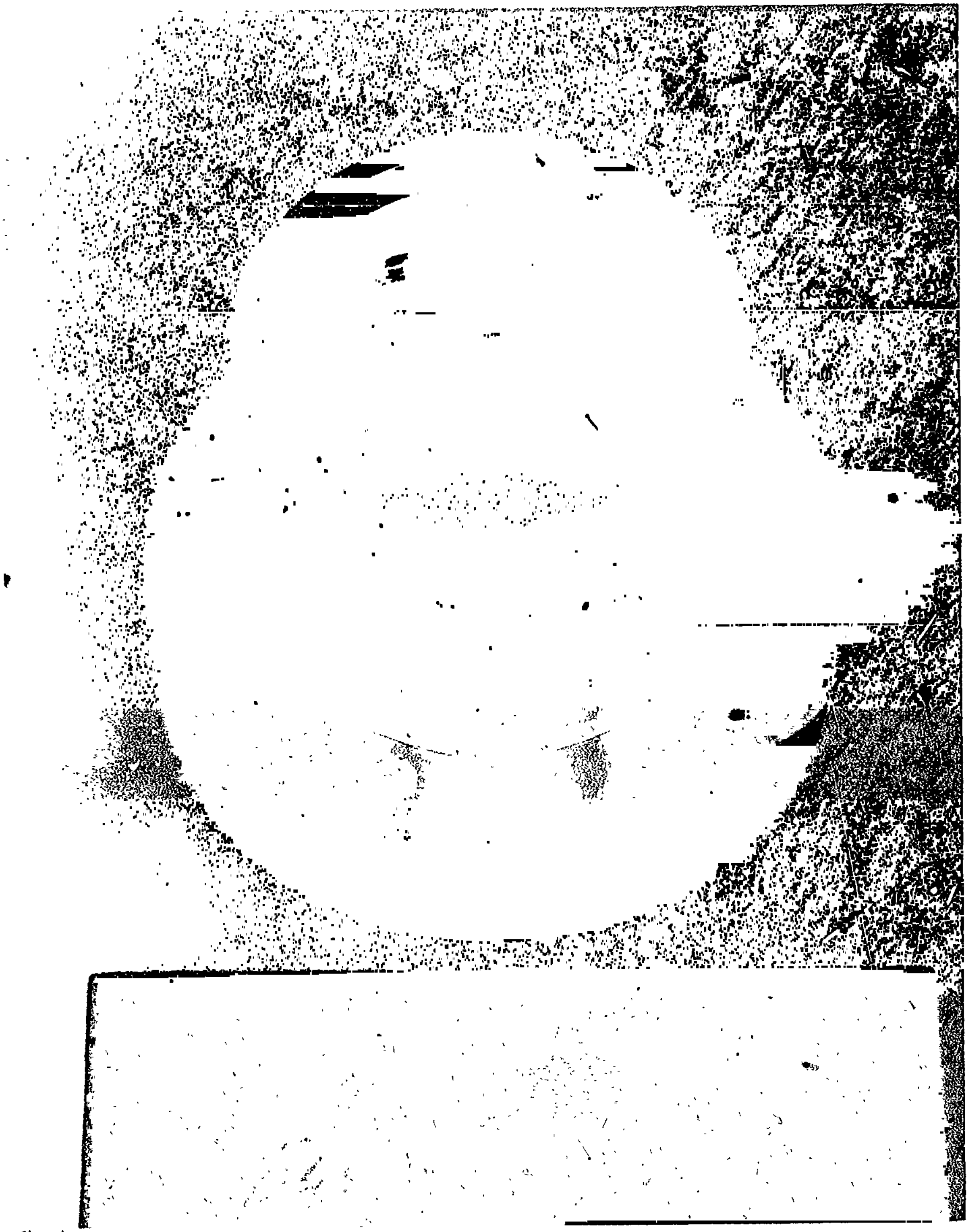
Figure 8



164-946

Test Section - 5 Threads/in.
(Tapered Groove Depth = 0.015-0.080 in.;
Groove Width = 0.110 in.; Land Width = 0.090 in.)

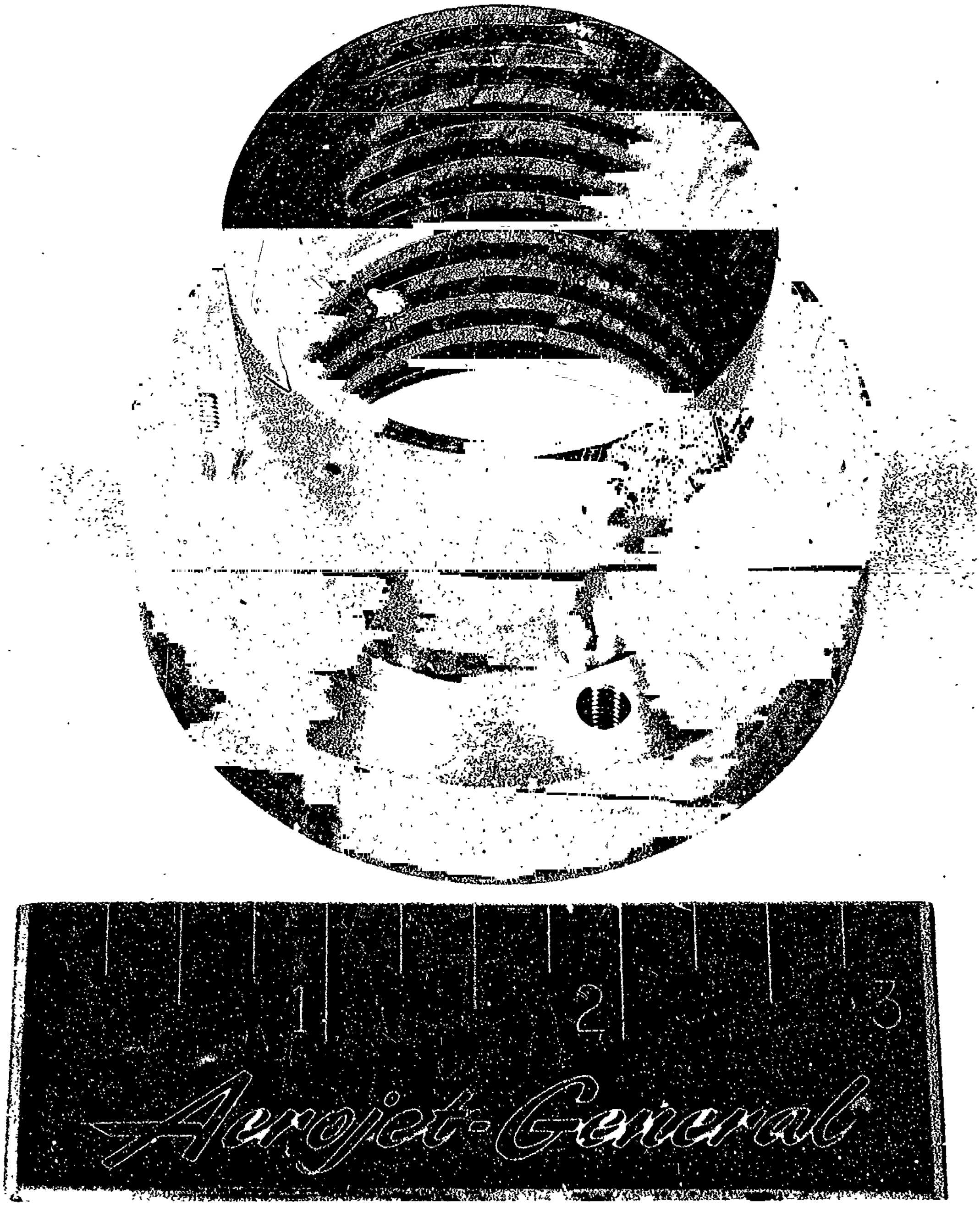
Figure 9



164-945

Test Section - 5 Threads/in.
(Pre-Molecular Pump Section; Groove Depths = 0.014 and 0.070 in.; Section Lengths = 0.50 and 1.40 in.; Groove Width = 0.110 in.; Land Width = 0.090 in.)

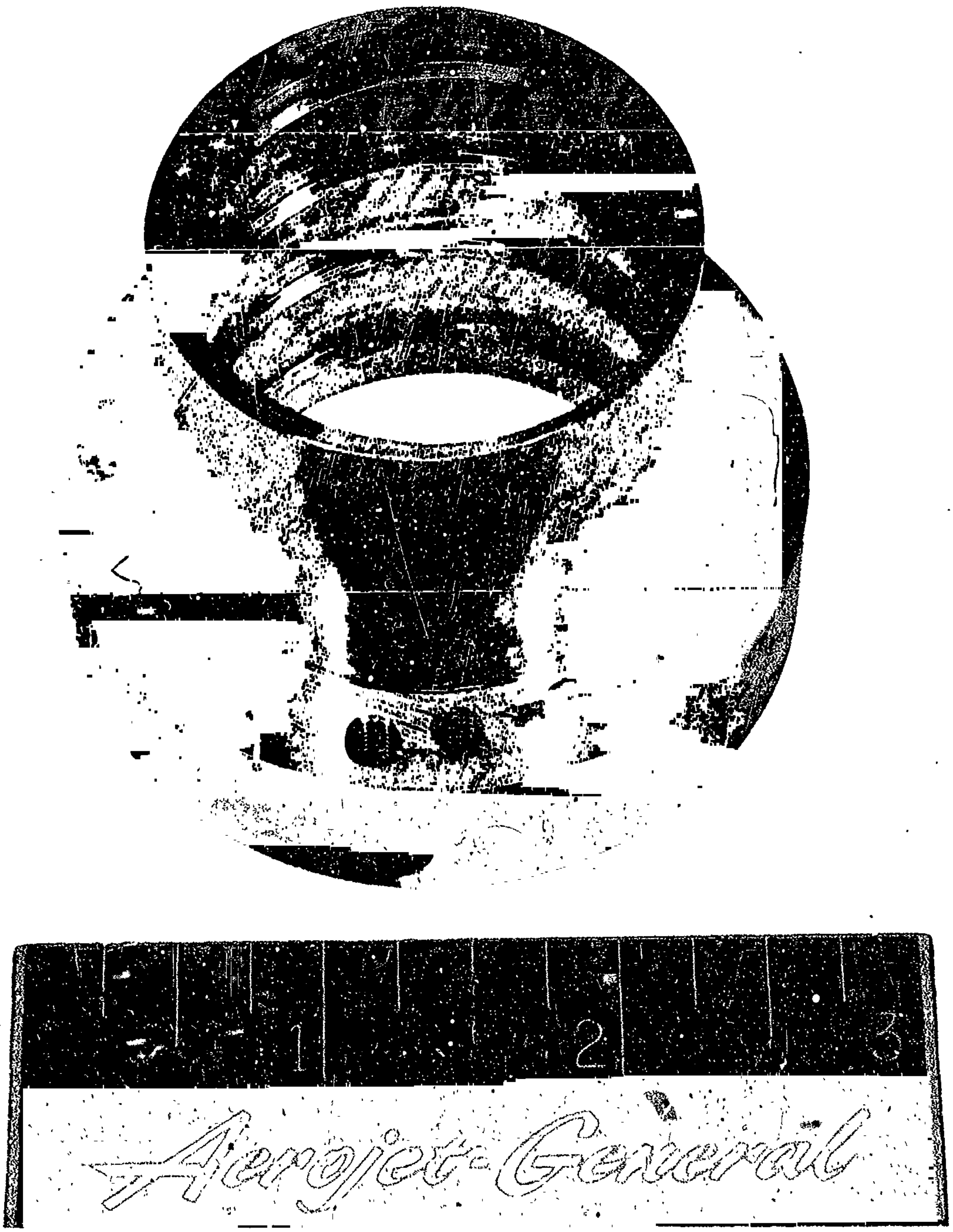
Figure 10



164-944

Test Section - 5 Threads/in.
(Constant Groove Depth = 0.070 in.;
Groove Width = 0.110 in.; Land Width = 0.090 in.)

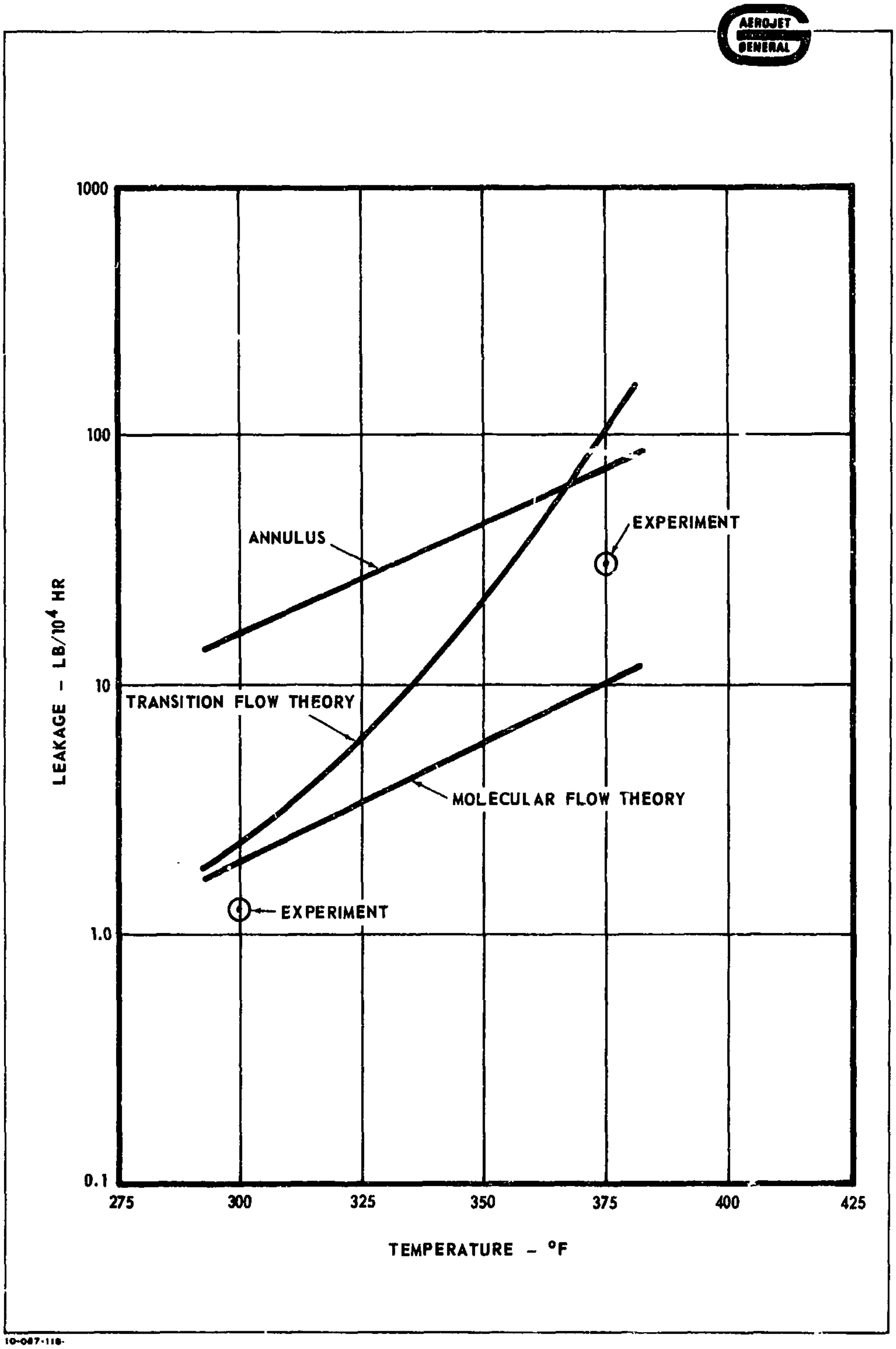
Figure 11



164-938

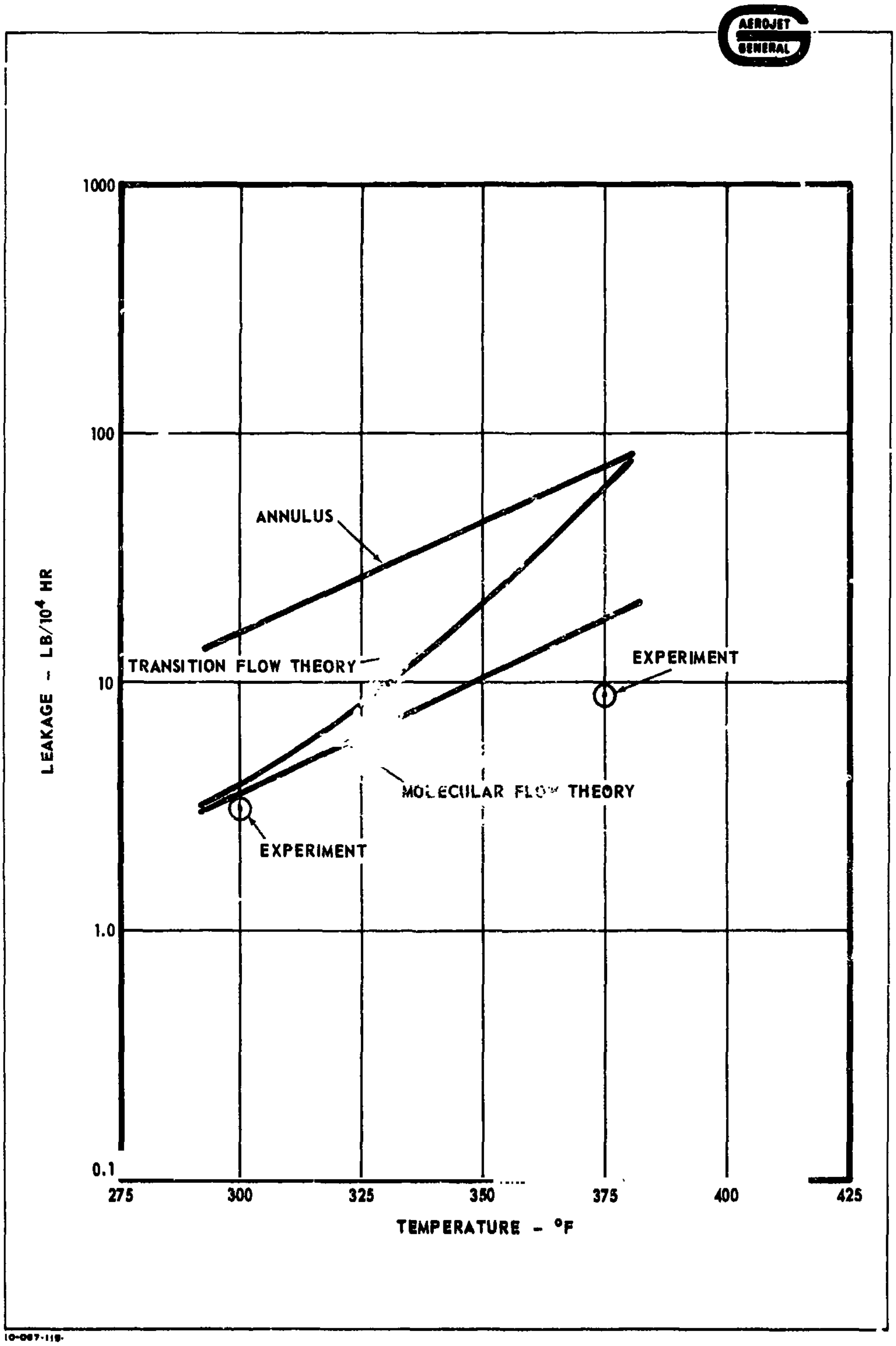
Test Section - 2 Threads/in.
(Constant Groove Depth = 0.080 in.;
Groove Width = 0.280 in.; Land Width = 0.220 in.)

Figure 12



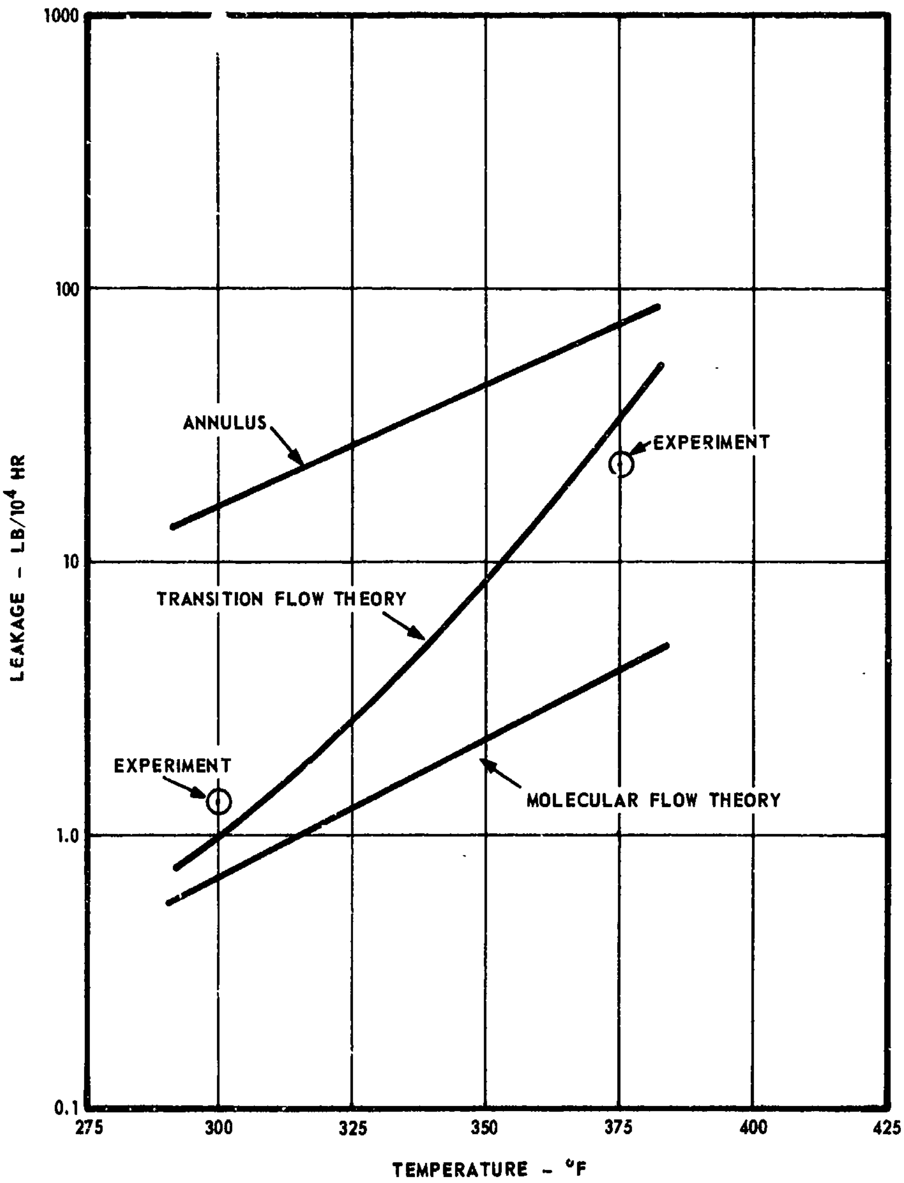
Leakage Data - 5 Threads/in.
(Constant Groove Depth = 0.070 in.; Groove Width = 0.110 in.; Radial Clearance = 0.0043 in.; Land Width = 0.090 in.)

Figure 13



Leakage Data - 5 Threads/in.
(Tapered Groove Depth = 0.015-0.080 in.; Groove Width = 0.110 in.; Radial Clearance = 0.0043 in.; Land Width = 0.090 in.)

Figure 14



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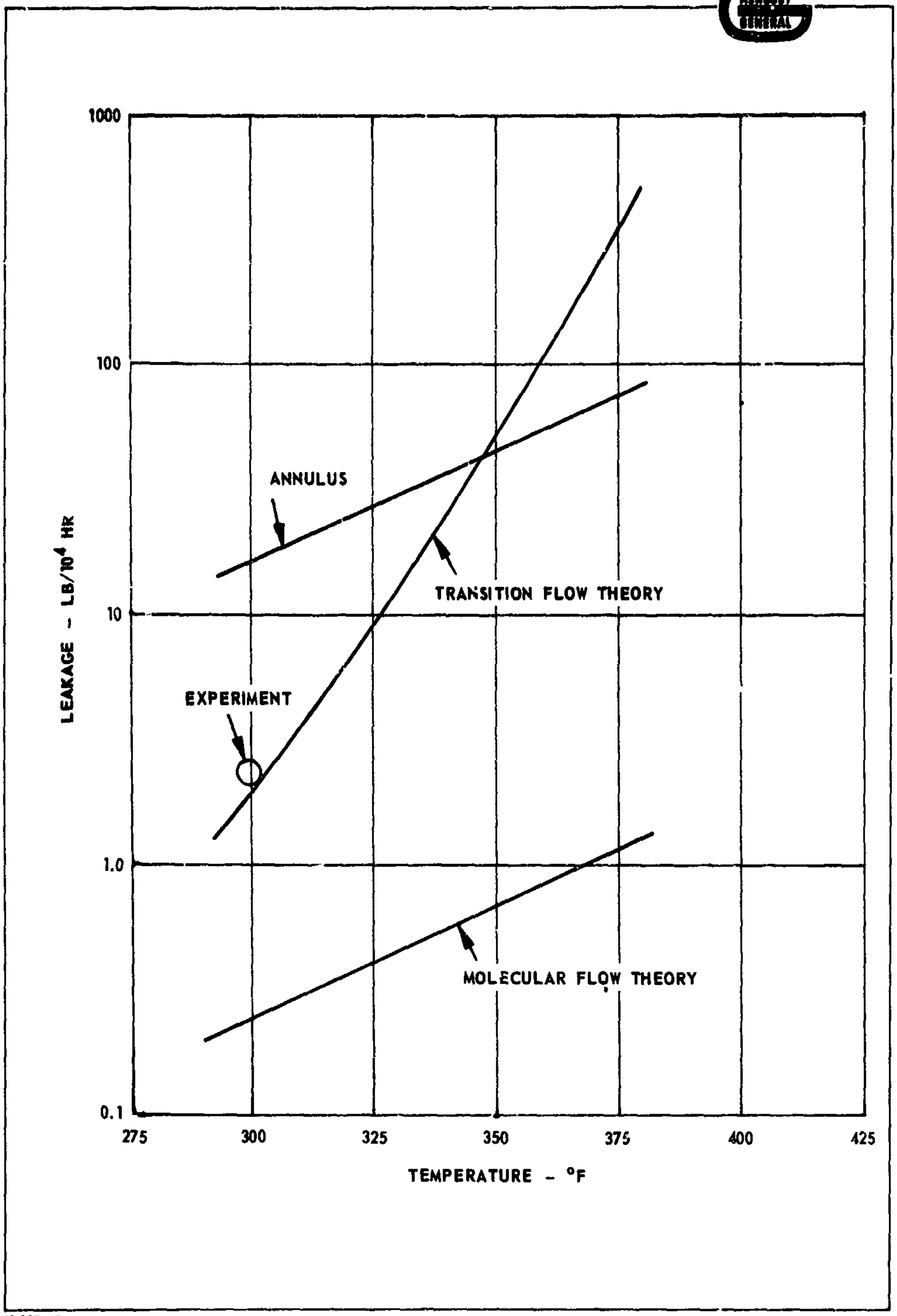
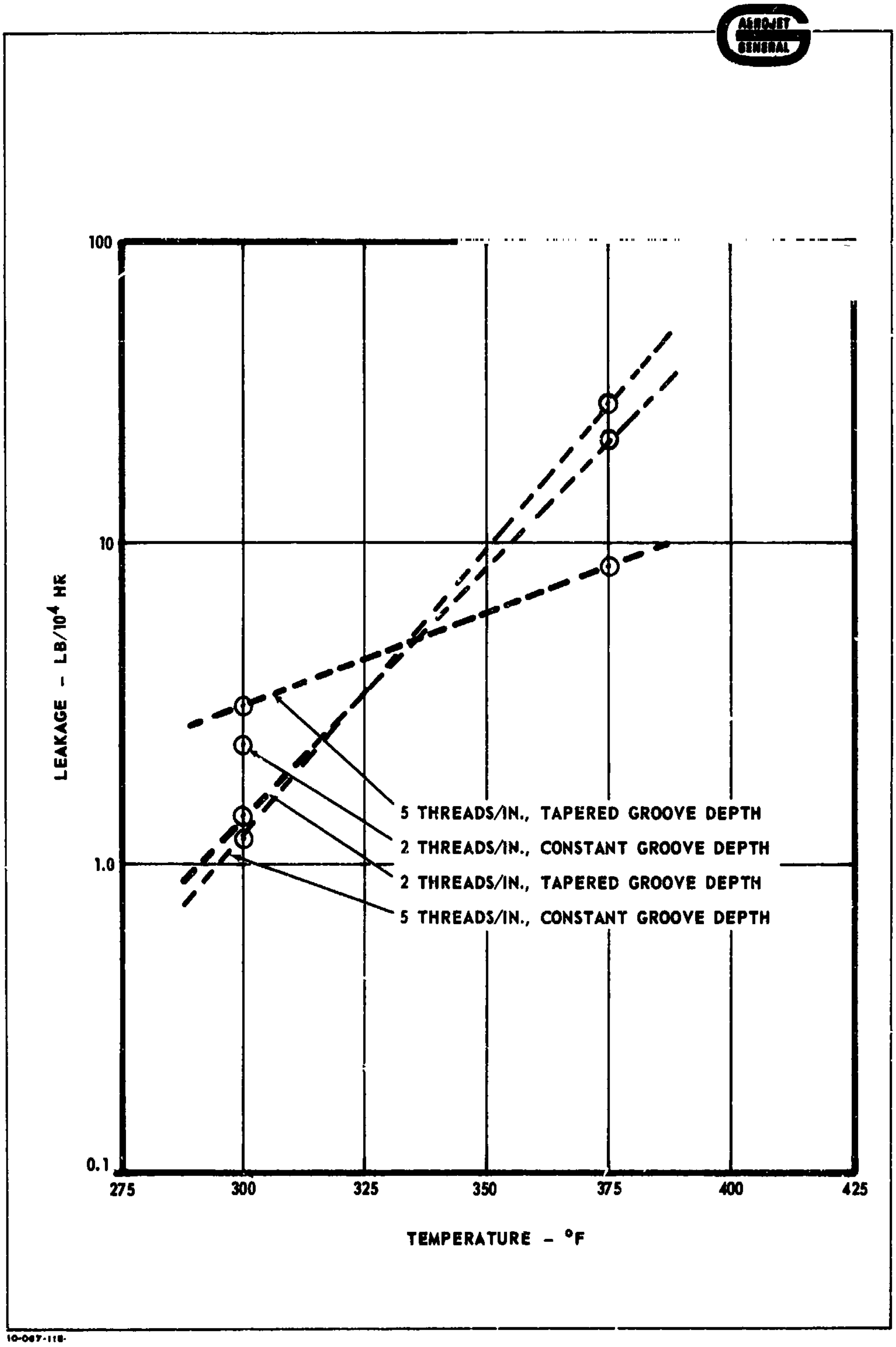
Leakage Data - 2 Threads/in.
(Tapered Groove Depth = 0.015-0.080 in.; Groove Width = 0.280 in.;
Radial Clearance = 0.0043 in.; Land Width = 0.220 in.)

Figure 15



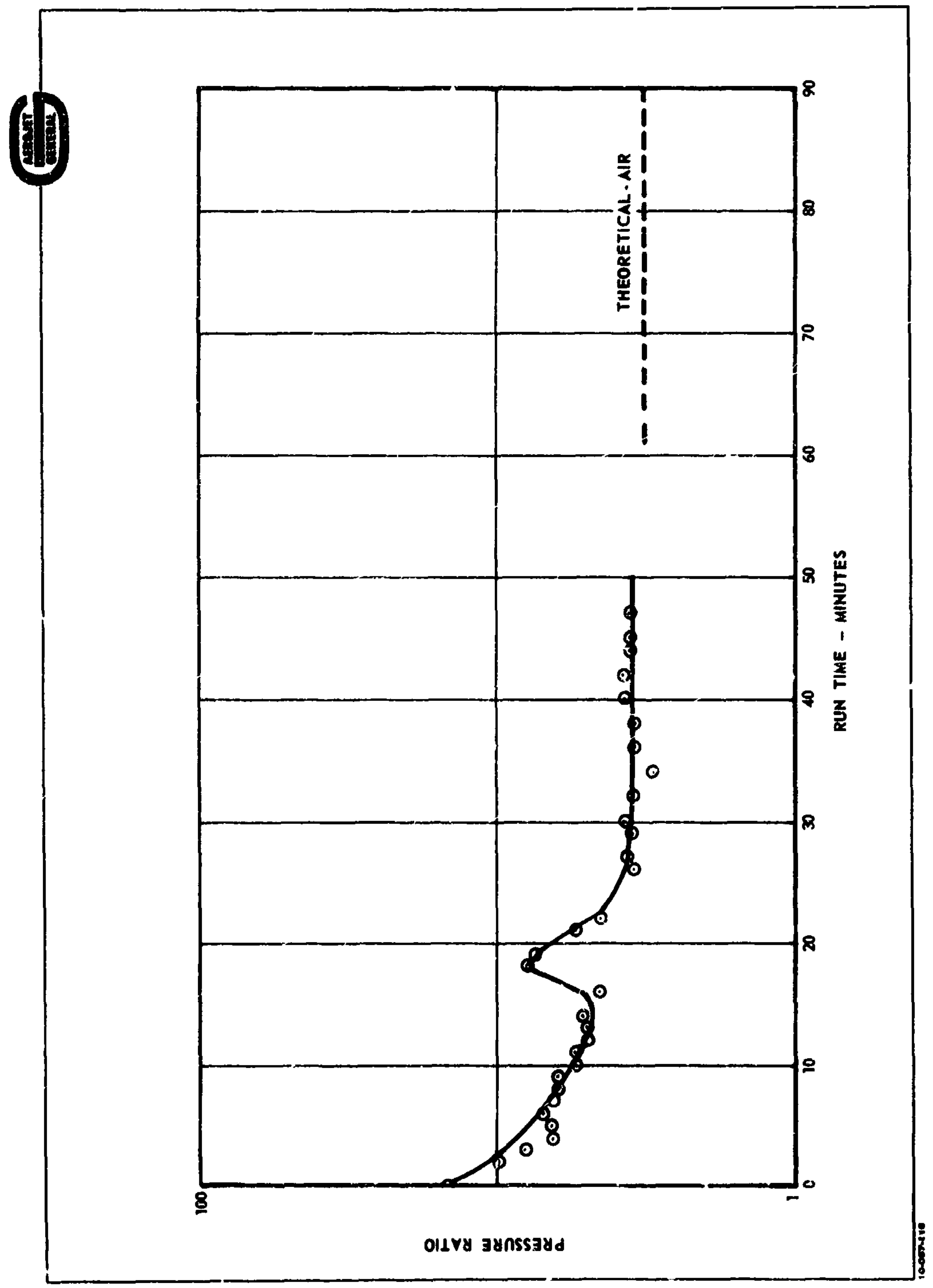
Leakage Data - 2 Threads/in.
(Constant Groove Depth = 0.080 in.; Groove Width = 0.280 in.;
Radial Clearance = 0.0043 in.; Land Width = 0.220 in.)

Figure 16



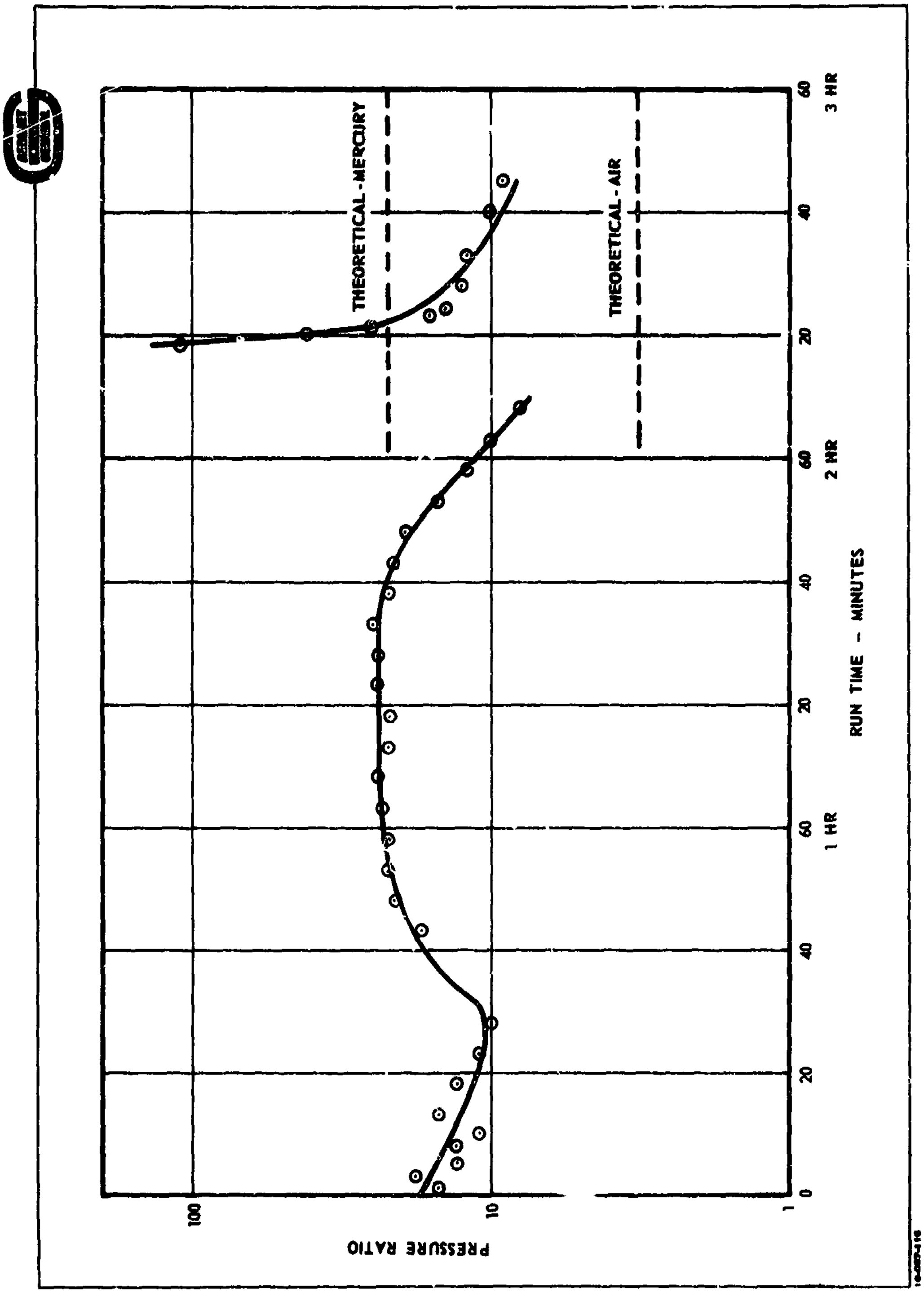
Comparison of Experimental Leakage Data

Figure 17



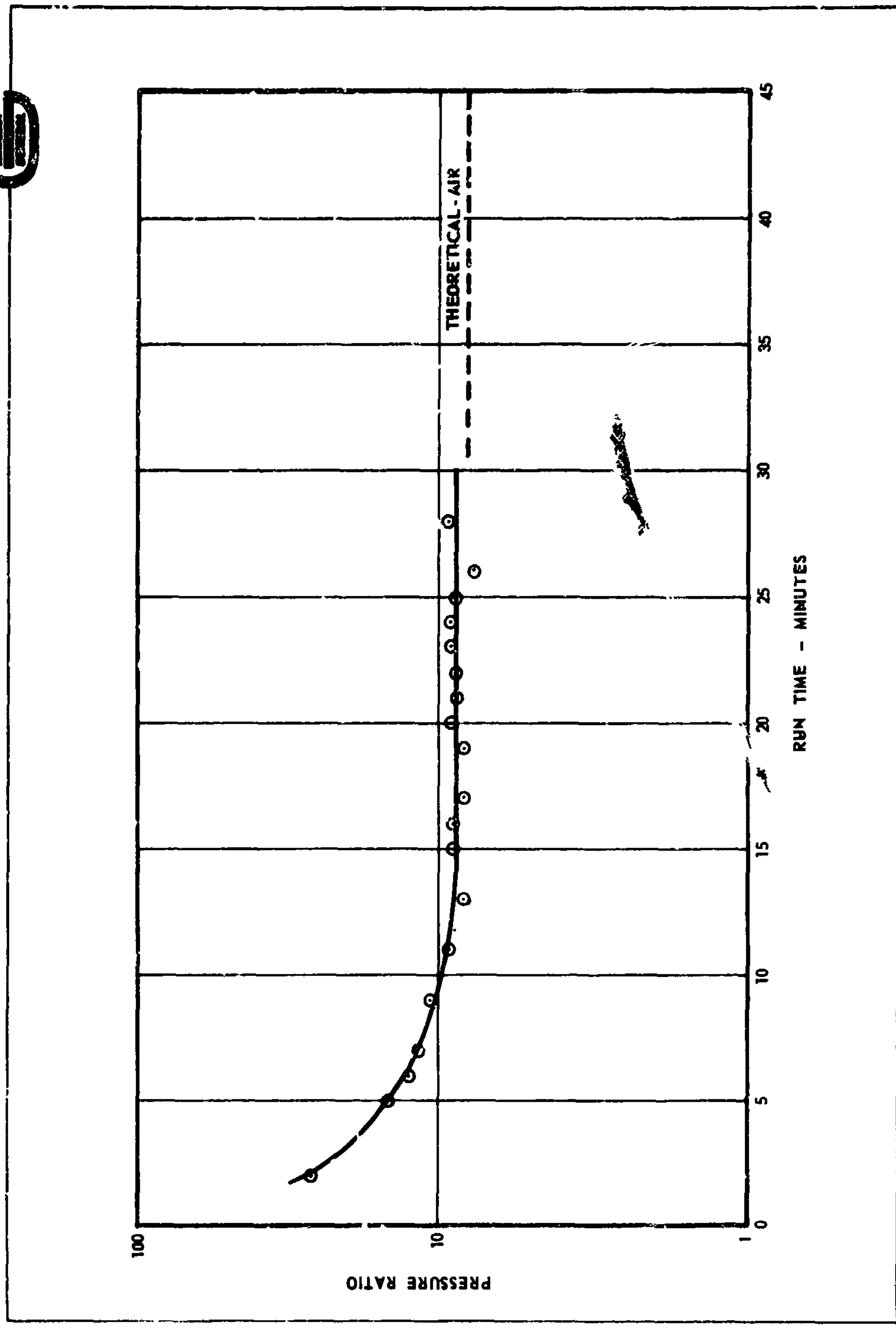
Pressure Ratio Data - Air (5 Threads/in.; Constant Groove Depth = 0.070 in.; 300°F; Groove Width = 0.110 in.; Land Width = 0.0[illegible]0 in.; Radial Clearance = 0.0043 in.)

Figure 18



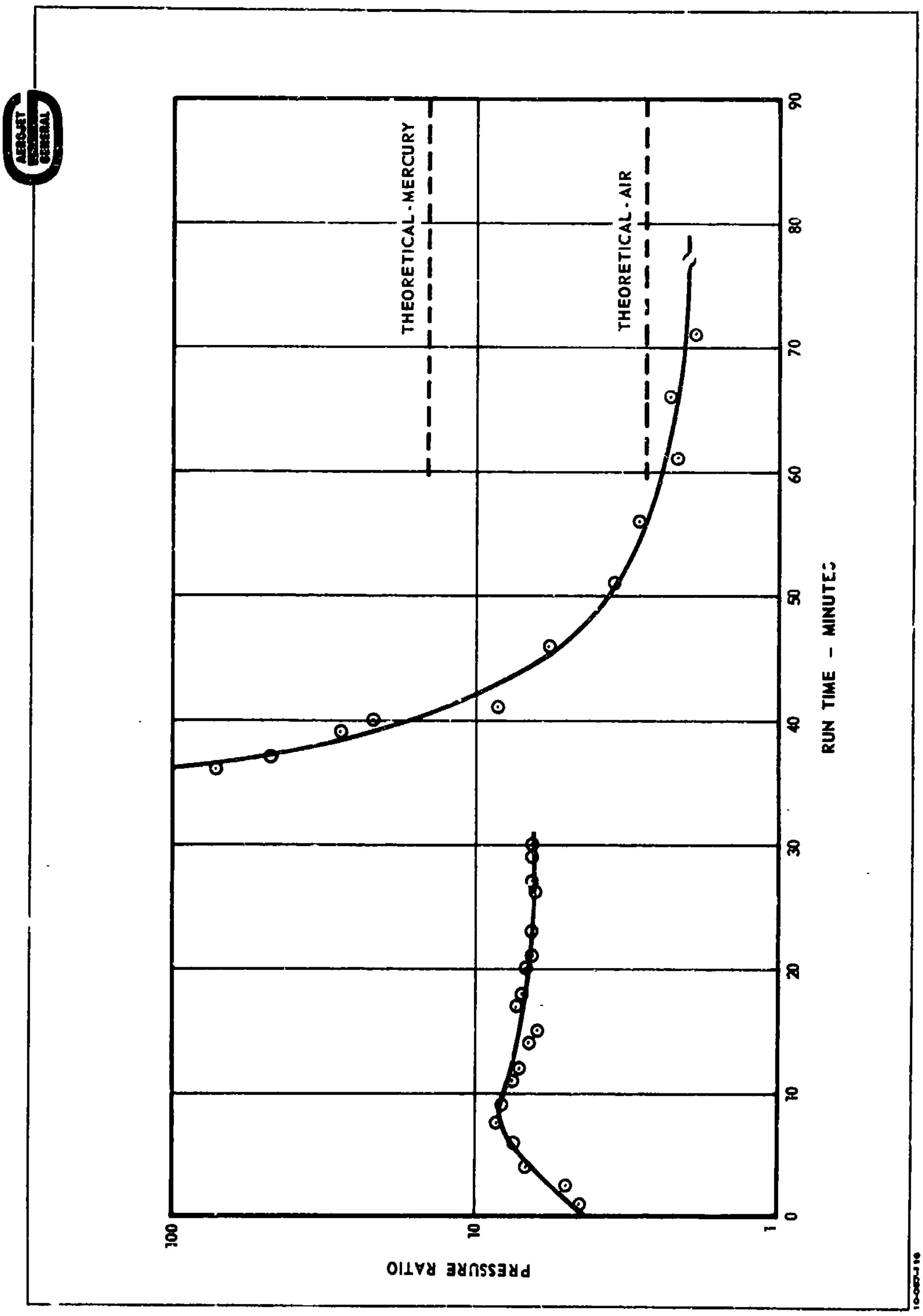
Pressure Ratio Data - Mercury (5 Threads/in.;
Constant Groove Depth = 0.070 in.; 300°F;
Groove Width = 0.110 in.; Radial Clearance = 0.0043 in.;
Land Width = 0.090 in.)

Figure 19



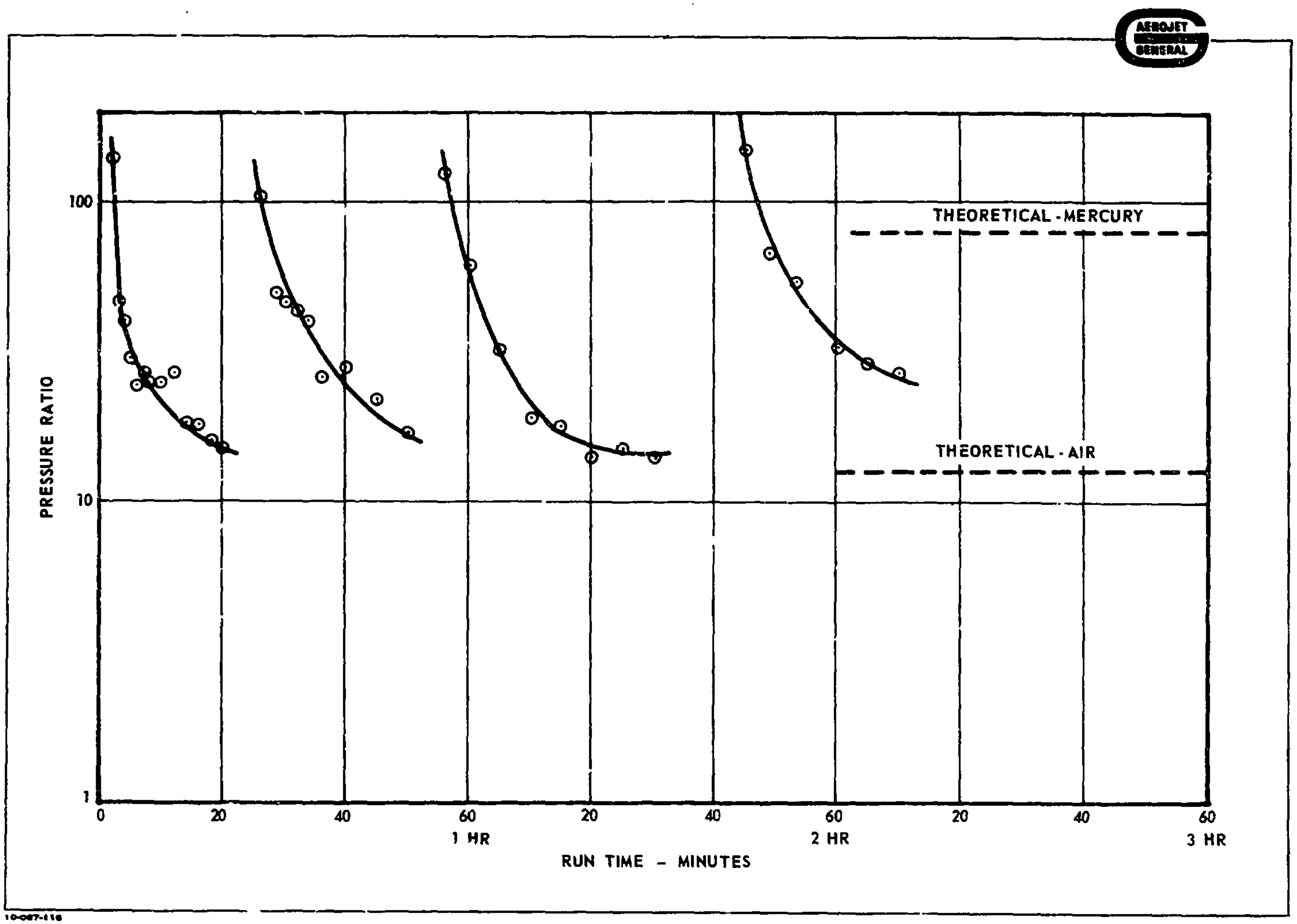
Pressure Ratio Data - Air (2 Threads/in.;
Tapered Groove Depth = 0.015-0.080 in.; 250°F;
Groove Width = 0.280 in.; Radial Clearance = 0.0043 in.;
Land Width = 0.220 in.)

Figure 20



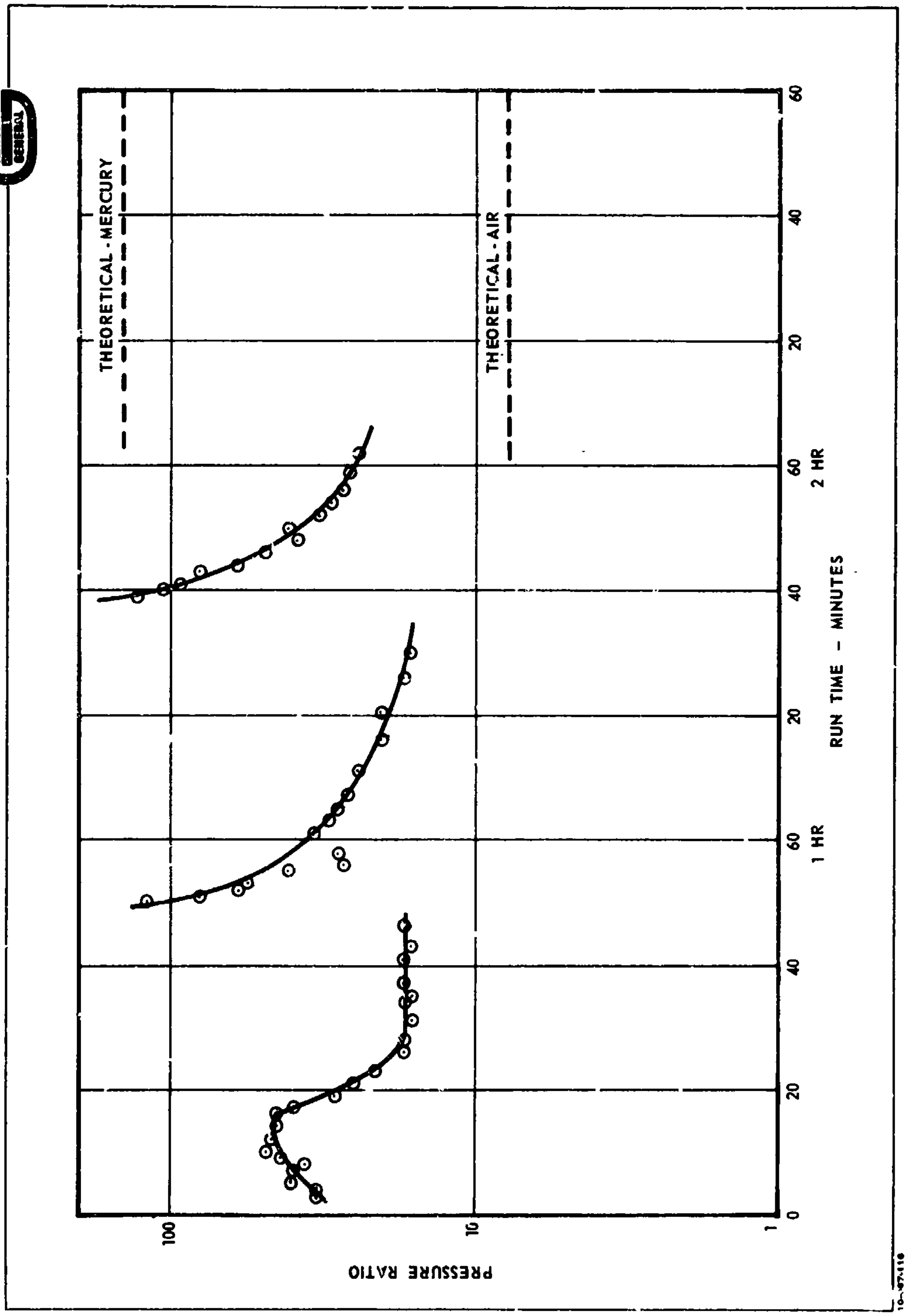
Pressure Ratio Data - Mercury (5 Threads/in.;
Tapered Groove Depth = 0.015-0.080 in.; 300°F;
Groove Width = 0.110 in.; Radial Clearance = 0.0043 in.;
Land Width = 0.090 in.)

Figure 21



Pressure Ratio Data - Mercury (2 Threads/in.;
Constant Groove Depth = 0.080 in.; 300°F;
Groove Width = 0.280 in.; Radial Clearance = 0.0043 in.;
Land Width = 0.220 in.)

Figure 22



Pressure Ratio Data - Mercury (2 Threads/in.;
Tapered Groove Depth = 0.015-0.080 in.; 300°F;
Groove Width = 0.280 in.; Radial Clearance = 0.0043 in.;
Land Width = 0.220 in.)

Figure 23

APPENDIX A

MOLECULAR FLOW THEORY OF THE MOLECULAR PUMP AND COMPUTER RESULTS

I. INTRODUCTION

The original concept of the molecular pump was as a vacuum pump. Ordinarily, the vacuum pump is thought of only as a means of evacuating a given volume. The speed with which this can be accomplished and the degree of vacuum attainable are functions of the pump type and quality. However, the vacuum pump can also serve effectively as a seal to maintain a pressure differential between two regions, thereby reducing the leakage rate of the fluid from the high-pressure region. The analysis to follow investigates the potential of the molecular pump as a sealing device.

The molecular pump falls within the class of vacuum pumps known as mechanical pumps. The distinguishing feature of the molecular pump with respect to others of this class is that the molecular pump has no rubbing contact of one part with another.

The molecular pump does not depend upon tight-fitting pistons, valves, etc. to separate the high and low pressure sides of the system; instead, it depends upon the pumping action effected by the motion of boundaries adjacent to the working fluid. The principle of operation is demonstrated in Figure A-1. The pump consists of a rotating shaft surrounded by a stationary casing into which is cut a helical groove. Molecules striking the moving surface acquire a velocity component in the direction of motion of the moving member, which results in an overall pumping action on the fluid.

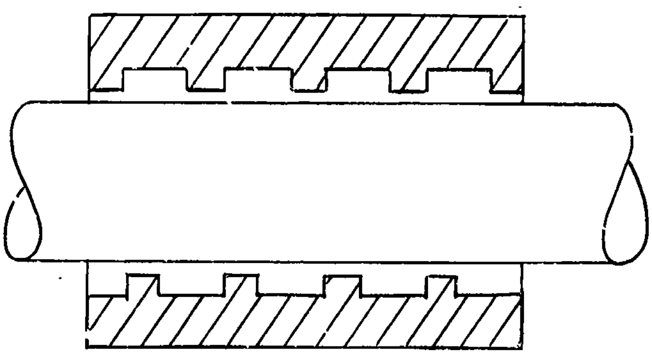


Figure A-1

The pump, as a complete system, has three basic flow components. The first, described above, is the motion along the helical path induced by the rotor. The second type flow is the reverse flow along the helical channel resulting from the pressure gradient developed within the channel. The third type flow is leakage over the channel lands. This latter flow is essentially axial. Like the reverse flow along the helical channel, the leakage flow is motivated by the pressure gradient within the pump. Each of these flow types is now considered separately and developed mathematically.

II. MATHEMATICAL FORMULATION

A. ROTOR-INDUCED FLOW

In the mathematical formulation of the problem it is assumed that the gas between the rotor and the stationary case is at a low enough density that the problem can be approached using simple laws derived from kinetic theory. The applicability of the laws is based upon maintaining the density low enough, or the gas layer thin enough, for molecules to travel from one boundary surface to another without collisions with other molecules (i.e., the mean free path is large compared with the dimensions of the confining surfaces).

In its most simple form, the rotor-induced flow is considered as a case of one plane surface moving parallel to a second stationary plane surface. Figure A-2 shows two plates which represent the rotor surface and the surface of the helical channel. The upper plate is moving with velocity U. With the assumption of molecular flow, each molecule, after striking one plate, moves at constant velocity until it strikes the other plate. Hence, if u_1 is the mean tangential component of velocity as the molecules leave the lower plate, this will also be their mean component as they arrive at the upper plate. Similarly, u_2 represents the mean tangential component of velocity for molecules as they leave the upper plate or arrive at the lower plate.

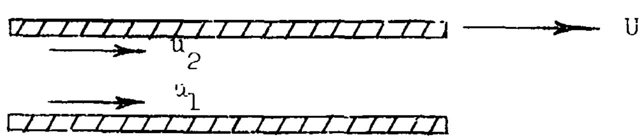


Figure A-2

It is necessary next to introduce the coefficient f which represents the fraction of tangential momentum possessed by a molecule that is transferred to a plate upon collision. The numerical value of f is a function of the conditions and type of reflection that occur at a boundary. For instance, if specular reflection were assumed, a molecule would strike a surface and reflect at an angle equal to its angle of incidence. The transfer of tangential momentum would be zero (i.e., $f = 0$). On the other hand, if diffuse reflection were assumed, a complete transfer of momentum would occur. That is, the molecule would essentially be absorbed at the surface and then be emitted at an angle completely independent of the angle of incidence. In this case, $f = 1.0$. Table A-1 (Reference 1) shows some typical values of the coefficient f for several combinations of gas and boundary surface material. In general, f is seen to be not far from unity.

TABLE A-1

Combination	f
Air or CO_2 on machined brass or old shellac	1.00
Air on mercury	1.00
Air on oil	0.89
CO_2 on oil	0.92
Hydrogen on oil	0.92
Air on glass	0.89
Helium on oil	0.87
Air on fresh shellac	0.79

Let f_1 and f_2 denote the coefficients of momentum transfer at the lower and upper plates, respectively. Letting M_1 equal the mass of vapor striking the upper plate per unit area per unit time, the momentum transferred to the upper plate is

$$M_1 f_2 (u_1 - U) \tag{1}$$

This also represents the amount of momentum lost by the molecules striking the upper plate. Therefore, the momentum transferred can also be written as

$$M_1 (u_1 - u_2) \tag{2}$$

From Equations (1) and (2),

$$u_1 - u_2 = f_2 (u_1 - U) \tag{3}$$

Similarly, for the lower plate

$$u_2 - u_1 = f_1 u_2 \tag{4}$$

From Equations (3) and (4)

$$u_1 = \frac{f_2(1 - f_1)}{f_1 + f_2 - f_1 f_2} U \tag{5}$$

$$u_2 = \frac{f_2}{f_1 + f_2 - f_1 f_2} U$$

In the actual application of the above principles to the molecular pump, the lower surface of Figure A-2 is a channel rather than a plane surface. Therefore, the average gas velocity is not simply

$$\frac{u_1 + u_2}{2}$$

It will be assumed, instead, that the velocity is a weighted average according to the areas of the stationary and moving surfaces. Figure A-3 shows a molecular pump with the defining nomenclature.

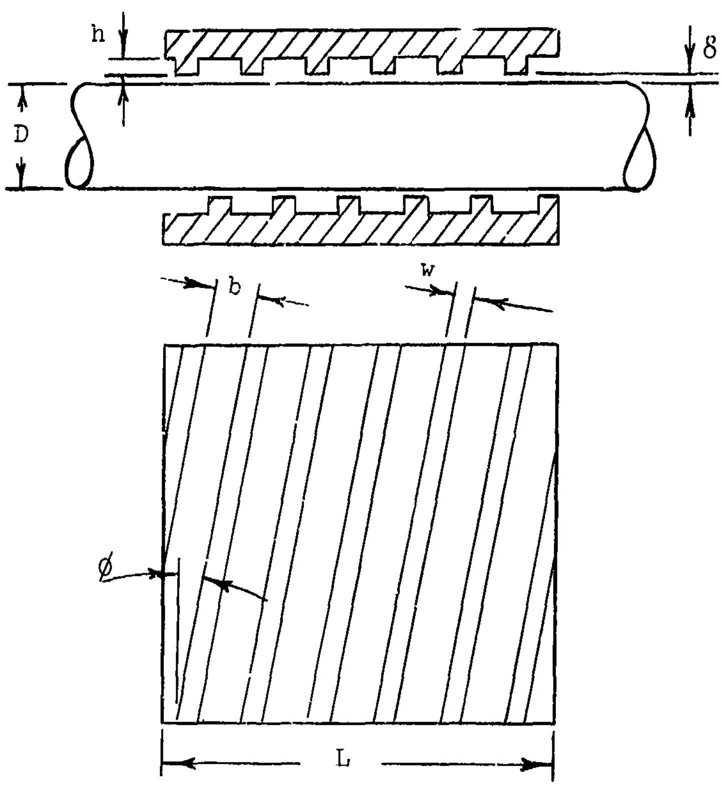


Figure A-3

Let a_1 be equal to the perimeter of the stationary surface perpendicular to the direction of fluid motion, and let a_2 be equal to the width of the moving surface perpendicular to the direction of fluid motion. Therefore, the weighted average flow velocity is

$$\bar{U} = \frac{u_1 a_1 + u_2 a_2}{a_1 + a_2} \text{ in./sec} \tag{6}$$

Letting $a_1 = (b + 2h)$

$a_2 = b$

where

b = channel width, in.

h = channel height, in.

Substituting these relationships into Equation (6) gives the average velocity as

$$\bar{U} = \frac{\dfrac{f_2(1 - f_1)}{f_1 + f_2 - f_1 f_2} U(b + 2h) + \dfrac{f_2}{f_1 + f_2 - f_1 f_2} Ub}{2\ (b + h)}$$

or

$$\bar{U} = \frac{U}{2(b + h)} \left[\frac{f_2(1 - f_1)(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2}\right] \tag{7}$$

The volume flow rate at unit pressure is

$$Q_D = \bar{U} bhp \tag{8}$$

where

Q_D = flow rate at unit pressure due to rotor motion, $\dfrac{\text{in.}^3}{\text{sec}} \quad \dfrac{\text{lb}}{\text{in.}^2}$

p = pressure, lb/in.^{2}

Combining Equations (7) and (8)

$$Q_D = \frac{Ubh}{2(b + h)} \left[\frac{f_2(1 - f_1)(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2}\right] p \tag{9}$$

The velocity, U, is a function of shaft speed, shaft diameter, and channel dimensions, and can be determined as shown below.

$$U = \frac{\pi DN}{60} \cos\phi \tag{10}$$

where

N = shaft speed, rpm

D = shaft diameter, in.

ϕ = helix angle

The angle ϕ is defined in Figure A-4 from which

$$\cos\phi = \frac{\left[(\pi D)^2 - (w + b)^2\right]^{1/2}}{\pi D} \tag{11}$$

where

w = channel ridge width, in.

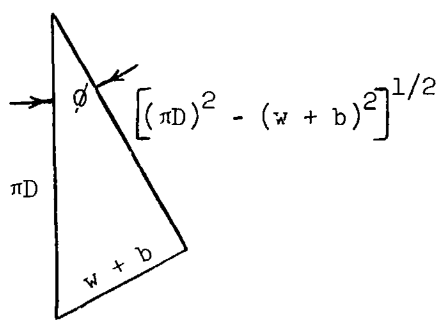


Figure A-4

Combining Equations (9), (10), and (11), the rotor-induced flow at unit pressure is

$$Q_D = \frac{Nbh}{120\ (b + h)} \left[\frac{f_2(1 - f_1)(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2}\right] \left[(\pi D)^2 - (w + b)^2\right]^{1/2} p \tag{12}$$

B. PRESSURE-INDUCED FLOW IN CHANNEL

The flow of a low-pressure gas in a passageway is derived from kinetic theory (Reference 2) as

$$Q_P = \frac{16}{3} K_1 \sqrt{\frac{k\,T}{2\pi m}} \frac{A^2}{B} \frac{dp}{d\ell} \tag{13}$$

where

Q_P = pressure-induced flow at unit pressure, $\frac{\text{in.}^3}{\text{sec}} \frac{\text{lb}}{\text{in.}^2}$

K_1 = constant determined by geometry

A = cross-sectional area perpendicular to flow, in.^{2}

B = perimeter of passageway perpendicular to flow, in.

ℓ = length along flow path, in.

T = temperature, $^{\circ}$R

m = mass of molecule, lb-sec^2/in.

k = Boltzmann constant, 6.78×10^{-23} in.-lb/$^{\circ}$R

p = pressure, lb/in.^{2}

The geometrical factor, K_1, is a function of the passageway length, area, etc. For a rectangular passageway, where the length is much greater than the cross-sectional dimensions, Reference 2 gives the factor K_1 as

$$K_1 = \frac{\frac{3}{8}(1+\gamma)}{\gamma^2} \left\{ \gamma \,\ell n \left(\gamma + \sqrt{1+\gamma^2} \right) + \gamma^2 \,\ell n \frac{1+\sqrt{1+\gamma^2}}{\gamma} + \frac{1}{3}\left[1 + \gamma^3 - (1+\gamma^2)^{3/2} \right] \right\} \tag{14}$$

where

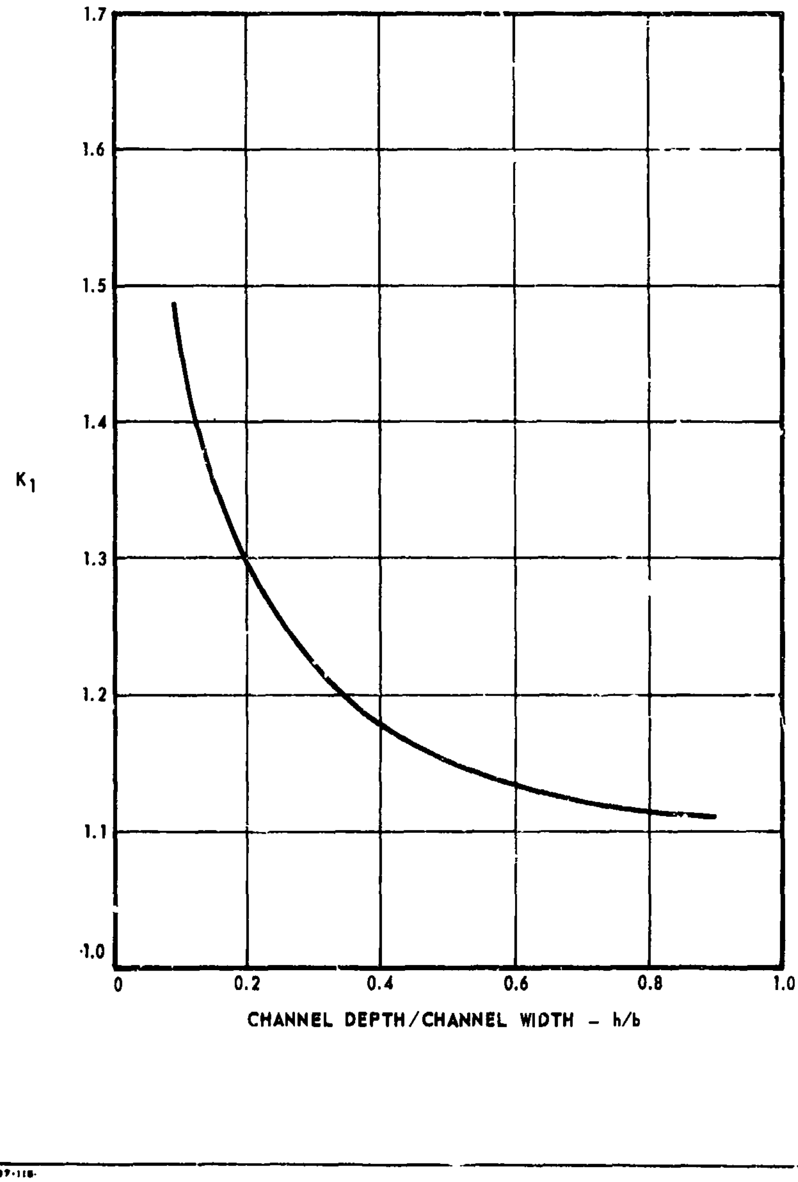
$$\gamma = \frac{h}{b}$$

Table A-2 below gives values computed from Equation (14).

TABLE A-2

γ	1	0.667	0.500	0.333	0.200	0.125	0.100
K_1	1.108	1.126	1.151	1.198	1.297	1.400	1.444

K_1 is plotted vs γ in Figure A-5.



Geometrical Factor, K_1, for Long Rectangular Tube

Figure A-5

The cross-sectional area and perimeter of the passageway are

$$A = bh \tag{15a}$$

$$B = 2(h + b) \tag{15b}$$

Substituting Equations (15a) and (15b) into Equation (13) gives the pressure-induced flow at unit pressure as

$$Q_P = \frac{8K_1}{3} \sqrt{\frac{k\ T}{2\pi m}} \quad \frac{(bh)^2}{(h + b)} \quad \frac{dp}{d\ell} \tag{16}$$

A relationship is next required between the pump length, L, and the channel length, ℓ. This relationship is shown in Equation (17).

$$\ell = \frac{\pi D n}{\cos\phi} \tag{17}$$

where

$$n = \text{number of turns of spiral} = \frac{L \cos\phi}{b + w}$$

Substituting in Equation (17) for n gives

$$\ell = \frac{\pi D L}{b + w}$$

and

$$d\ell = \frac{\pi D\ dL}{b + w} \tag{18}$$

Combining Equations (16) and (18) gives the pressure-induced flow at unit pressure as

$$Q_P = \frac{8K_1(w + b)(bh)^2}{3\pi D(h + b)} \quad \sqrt{\frac{kT}{2\pi m}} \quad \frac{dp}{dL} \tag{19}$$

C. LEAKAGE FLOW RATE

The final type flow to be considered in the molecular pump is the leakage flow. The leakage flow is an axial flow over the ridges of the channel. The analysis of this flow is similar to that for the preceding pressure-induced flow. The flow rate is again given from kinetic theory as

$$Q_L = \frac{16}{3}\ K_2 \sqrt{\frac{kT}{2\pi m}} \quad \frac{A^2}{B} \quad \frac{dp}{d\ell} \tag{20}$$

In this case, the flow passageway is the clearance space between a channel ridge and the rotor. When viewed in the direction of flow, this passageway is a short, slit-like tube. Values of the constant K_2 for a slit-like tube are given in Reference 2 and are repeated as Table A-3 where δ = radial clearance, in.

TABLE 3

$\frac{w}{\delta}$	0.1	0.2	0.4	0.8	1	2	3	4	5	10
K_2	0.036	0.068	0.13	0.22	0.26	0.40	0.52	0.60	0.67	0.94

When $w/\delta > 10$, $K_2 = \frac{3}{8} \ln \frac{w}{\delta}$. K_2 is plotted vs w/δ in Figure A-6.

The cross-sectional area and perimeter of the leakage flow passageway are, respectively,

$$A = \left(\frac{\pi D \delta}{\cos\phi}\right) \tag{21a}$$

$$B = 2\left(\frac{\pi D}{\cos\phi} + \delta\right) \simeq \left(\frac{2\pi D}{\cos\phi}\right) \tag{21b}$$

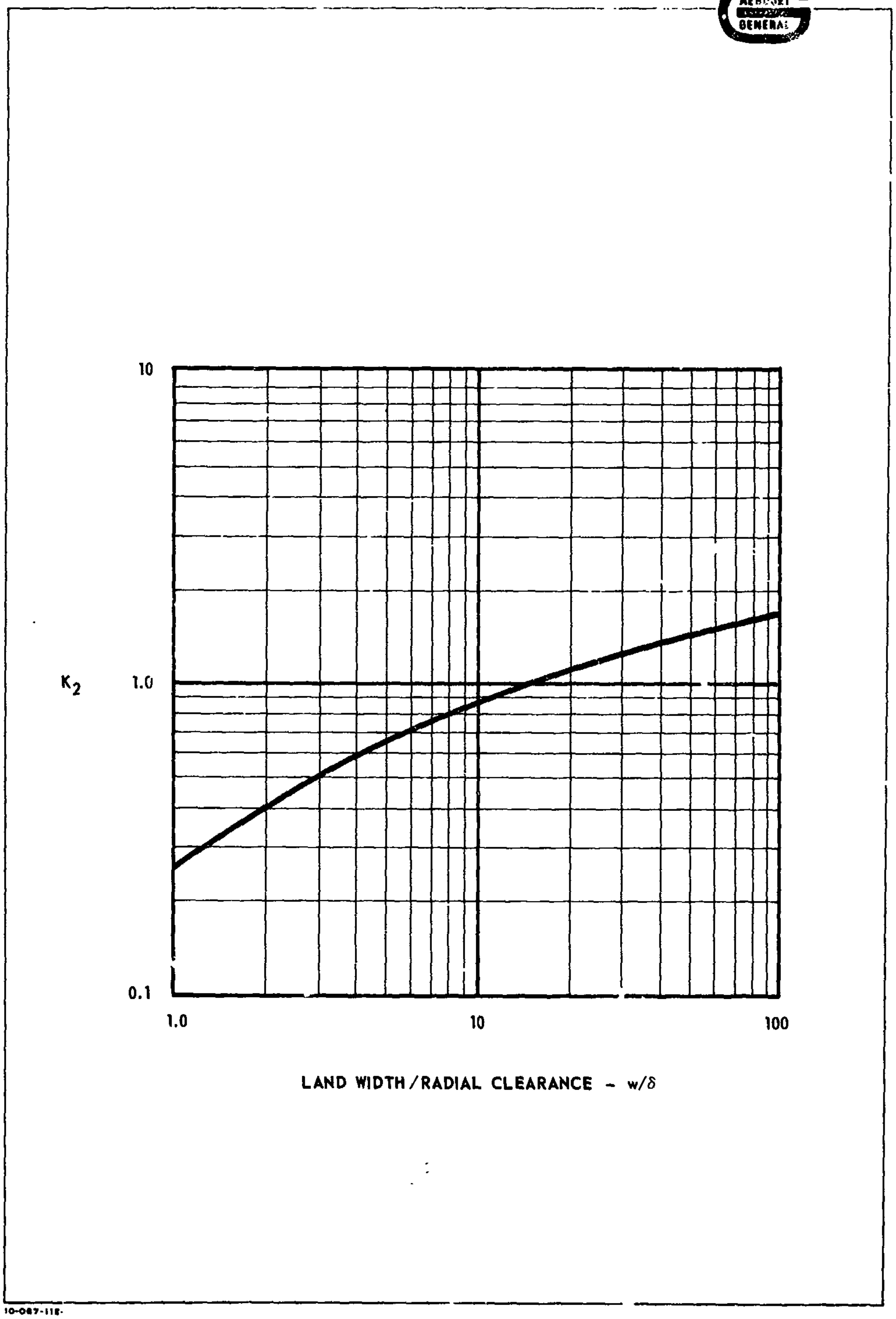
Next, the relationship between $dp/d\ell$ and dp/dL is required. It will be assumed that the pressure gradient varies continuously along the helical channel. Moving axially, then, the pressure gradient has a discontinuity at the beginning and end of each turn of the channel. It will be assumed that the pressure gradient is zero across a channel in a plane perpendicular to the channel axis. Referring to Figure A-7, this means the pressure is the same at points a and b. Therefore, the pressure gradient from b to c is $(w + b)/w$ times the pressure gradient from a to c. The relationship between the pressure gradient from a to c and the axial pressure gradient, dp/dL, is next needed.

The pressure difference from a to c differs from the pressure difference from a to d by the ratio of the respective lengths along the channel, i.e.,

$$\left(\frac{\frac{\pi D}{\cos\phi} - \pi D \tan\phi \sin\phi}{\frac{\pi D}{\cos\phi}}\right) = \cos^2\phi$$

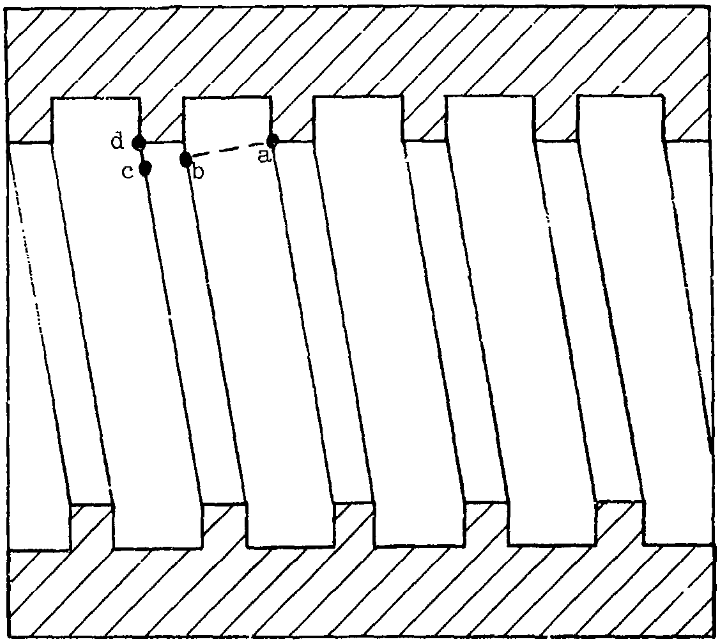
At the same time, the direct axial lengths a-c and a-d differ by $\cos\phi$. Therefore, the pressure gradients differ by the ratio $\cos^2\phi/\cos\phi = \cos\phi$ and the pressure gradient for leakage over the lands is

$$\frac{dp}{d\ell} = \frac{w + b}{w} \cos\phi \frac{dp}{dL} \tag{22}$$



Geometrical Factor, K_2, for Long Slit-Like Tube

Figure A-6



Land-Leakage Pressure Gradient Determination

Figure A-7.

Combining Equations (20), (21), and (22) gives the leakage flow rate at unit pressure as

$$Q_L = \frac{8K_2\,(\pi D)\,\delta^2\,(w + b)}{3w} \sqrt{\frac{kT}{2\pi m}} \; \frac{dp}{dL} \tag{23}$$

D. NET FLOW

The net flow through the pump is the flow induced by the rotor motion minus the pressure-induced channel flow and the leakage flow, or

$$Q_N = Q_D - Q_P - Q_L$$

Introducing Equations (12), (19), and (23) gives

$$Q_N = \frac{Nbh}{120(b + h)} \left[\frac{f_2(1 - f_1)(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2}\right] \left[(\pi D)^2 - (w + b)^2\right]^{1/2} p$$

$$- \frac{8K_1 (w + b)(bh)^2}{3\pi D\,(h + b)} \sqrt{\frac{kT}{2\pi m}}\;\frac{dp}{dL} - \frac{8K_2(\pi D)\delta^2(w + b)}{3w} \sqrt{\frac{kT}{2\pi m}}\;\frac{dp}{dL}$$

or

$$Q_N = \frac{Nbh}{120(b + h)} \left[\frac{f_2(1 - f_1)(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2}\right] \left[(\pi D)^2 - (w + b)^2\right]^{1/2} p$$

$$- \frac{8(w + b)}{3\pi D} \sqrt{\frac{kT}{2\pi m}} \left[\frac{K_1 (bh)^2}{(h + b)} + \frac{K_2(\pi D\delta)^2}{w}\right] \frac{dp}{dL}$$

or

$$Q_N = \alpha p - \beta \frac{dp}{dL} \tag{24}$$

where

$$\alpha = \frac{Nbh}{120(h + b)} \left[\frac{f_2(1 - f_1)(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2}\right] \left[(\pi D)^2 - (w + b)^2\right]^{1/2}$$

$$\beta = \frac{8(w + b)}{3\pi D} \sqrt{\frac{kT}{2\pi m}} \left[\frac{K_1 (bh)^2}{(h + b)} + \frac{K_2(\pi D\delta)^2}{w}\right]$$

Rearranging Equation (24),

$$\frac{dp}{dL} - \frac{\alpha}{\beta} p = - \frac{Q_N}{\beta}$$

Integrating,

$$p = e^{\int \frac{\alpha}{\beta} dL} \left[- \int \frac{Q_N}{\beta} e^{-\int \frac{\alpha}{\beta} dL} dL + C \right]$$

$$p = e^{\frac{\alpha L}{\beta}} \left[- \frac{Q_N}{\beta} \int e^{-\frac{\alpha L}{\beta}} dL + C \right]$$

$$p = e^{\frac{\alpha L}{\beta}} \left[\frac{Q_N}{\alpha} e^{-\frac{\alpha L}{\beta}} + C \right]$$

$$p = \frac{Q_N}{\alpha} + C e^{\frac{\alpha L}{\beta}}$$

When $L = 0$, $p = p_e$

When $L = L$, $p = p_o$

where

p_e = exit pressure (low pressure)

p_o = inlet pressure (high pressure)

Therefore,

$$C = p_e - \frac{Q_N}{\alpha}$$

and

$$p_o = \frac{Q_N}{\alpha} + (p_e - \frac{Q_N}{\alpha}) e^{\frac{\alpha L}{\beta}}$$

Solving for Q_N

$$Q_N = \alpha \left[\frac{p_o - p_e e^{\frac{\alpha L}{\beta}}}{1 - e^{\frac{\alpha L}{\beta}}} \right] \qquad (25)$$

Equation (25) is the flow rate at unit pressure. The weight flow rate is

$$\frac{Q_N}{p} \rho = \frac{Q_N}{RT} \tag{26}$$

where

R = gas constant = $\frac{18,550}{M}$ in./°R

M = molecular weight

ρ = density, lb/in.^{3}

From Equations (25) and (26), the weight flow rate is

$$W_N = \frac{\alpha}{RT} \left[\frac{p_o - p_e e^{\frac{\alpha L}{\beta}}}{1 - e^{\frac{\alpha L}{\beta}}} \right] \tag{27}$$

where

$$\alpha = \frac{Nbh}{120(b + h)} \left[\frac{f_2(1 - f_1)(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2} \right] \left[(\pi D)^2 - (w + b)^2 \right]^{1/2}$$

$$\beta = \frac{8(w + b)}{3\pi D} \sqrt{\frac{kT}{2\pi m}} \left[\frac{K_1 (bh)^2}{(h + b)} + \frac{K_2 (\pi D \delta)^2}{w} \right]$$

Equation (27) defines the weight flow rate through a molecular pump. The equation is applicable whether the pump is acting as a vacuum pump or as a seal. A positive value of W_N indicates flow from low to high pressure, and a negative value indicates flow from high to low pressure. When being used as a vacuum pump, the weight flow rate always has a positive value until the pressure ratio reaches its maximum value at which time the flow rate is zero. This maximum pressure ratio is derived in the following section. When the molecular pump is acting as a seal-to-space, the pressure ratio imposed on it is greater than the maximum it can develop as a pump, and there is a flow, or leakage, from the high-pressure side through the pump and out to the low-pressure region.

The situation of zero leakage, or perfect sealing, is possible only when the low-pressure side of the pump opens into a vessel of set volume. With a set volume, the pump will eventually reach its maximum pressure ratio, and the net flow through the pump becomes zero. For a seal-to-space, however, the volume on the low-pressure side is infinite; hence there is always a net leakage rate through the pump, and Equation (27) always has a negative value.

The maximum pressure ratio that the pump can develop is only of academic interest when the pump is serving as a seal-to-space since, by definition, the maximum pressure ratio occurs at zero leakage - an impossible condition. The actual pressure ratio on the pump will be very large. It will not, however, be infinite unless the pump discharges directly to space without any intervening passageways. In molecular flow, the rate of discharge through a passageway is not a function of downstream pressure, and a pressure will exist in any passageway connecting the pump and space. The outlet passageway will usually be of sufficiently low resistance, however, that the assumption of an infinite pressure ratio is appropriate. Therefore, setting p_e equal to 0 in Equation (27) gives the leakage flow rate for sealing directly to space.

E. MAXIMUM PRESSURE RATIO

The maximum pressure ratio the molecular pump can develop when operating as a pump is found by setting Q_N equal to 0 in Equation (24) to give

$$\frac{dp}{dL} = \frac{\alpha}{\beta} p$$

or

$$\frac{dp}{p} = \frac{\alpha}{\beta} dL$$

Integrating,

$$\ln p = \frac{\alpha}{\beta} L + C$$

When $L = 0$, $p = p_{e_o}$ = exit pressure at zero flow; when $L = L$, $p = p_o$.

Therefore, $C = \ln p_{e_o}$ and the maximum pressure ratio is

$$\frac{p_o}{p_{e_o}} = e^{\frac{\alpha L}{\beta}} \tag{28}$$

where

$$\alpha = \frac{Nbh}{120(h + b)} \left[\frac{f_2(1 - f_1)(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2}\right] \left[(\pi D)^2 - (w + b)^2\right]^{1/2}$$

$$\beta = \frac{8(w + b)}{3\pi D} \sqrt{\frac{kT}{2\pi m}} \left[\frac{K_1(bh)^2}{(h + b)} + \frac{K_2(\pi D\delta)^2}{w}\right]$$

III. COMPUTER ANALYSIS

The leaka~e rate through a molecular pump is defined by Equation (27). There are three variables which define the pump geometry: groove depth, groove width, and land width. Optimization of these three variables for various combinations of molecular weight, diameter, speed, temperature, length, and radial clearance has been conducted on an IBM-7090 computer. The resulting optimum dimensions, pressure ratios, and leakage rates for the various combinations of input conditions are tabulated on the following pages.

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER IN.	SPEED RPM	TEMP. °R	LENGTH IN.	(IN.) RADIAL CLEARANCE	GROVE WIDTH (IN.)	LAND WIDTH (IN.)	GROVE DEPTH (IN.)	PRESSURE RATIO	LEAKAGE LB/10" HR
200.6	1.3125	7800.	660.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.080E 00	-1.953E 00
200.6	1.3125	7800.	660.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.134E 00	-1.162E 00
200.6	1.3125	7800.	660.	0.50	0.002	0.10	1.971E-01	4.053E-02	4.407E 00	-4.952E-01
200.6	1.3125	7800.	660.	0.50	0.001	0.10	1.125E-01	4.053E-02	4.152E 01	-4.163E-02
200.6	1.3125	7800.	660.	1.00	0.004	0.14	2.827E-01	5.675E-02	4.666E 00	-9.020E-01
200.6	1.3125	7800.	660.	1.00	0.003	0.14	2.120E-01	5.675E-02	1.008E 01	-3.641E-01
200.6	1.3125	7800.	660.	1.00	0.002	0.14	1.692E-01	5.675E-02	4.756E 01	-7.102E-02
200.6	1.3125	7800.	660.	1.00	0.001	0.14	1.125E-01	3.957E-02	2.743E 03	-9.213E-04
200.6	1.3125	7800.	660.	1.50	0.004	0.18	2.269E-01	7.296E-02	1.741E 01	-3.330E-01
200.6	1.3125	7800.	660.	1.50	0.003	0.20	2.120E-01	5.653E-02	5.391E 01	-9.745E-02
200.6	1.3125	7800.	660.	1.50	0.002	0.18	1.692E-01	5.088E-02	4.285E 02	-9.769E-03
200.6	1.3125	7800.	660.	1.50	0.001	0.14	1.125E-01	3.957E-02	1.437E 05	-1.758E-05
200.6	1.3125	7800.	660.	2.00	0.004	0.20	1.712E-01	8.107E-02	5.656E 01	-1.215E-01
200.6	1.3125	7800.	660.	2.00	0.003	0.20	2.120E-01	5.653E-02	2.037E 02	-2.544E-02
200.6	1.3125	7800.	660.	2.00	0.002	0.18	1.692E-01	5.088E-02	3.231E 03	-1.293E-03
200.6	1.3125	7800.	660.	2.00	0.001	0.14	1.125E-01	3.957E-02	7.527E 06	-3.357E-07
200.6	1.3125	12000.	660.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.126E 00	-1.912E 00
200.6	1.3125	12000.	660.	0.50	0.003	0.12	2.538E-01	4.864E-02	4.629E 00	-1.030E 00
200.6	1.3125	12000.	660.	0.50	0.002	0.12	1.692E-01	4.864E-02	1.493E 01	-2.682E-01
200.6	1.3125	12000.	660.	0.50	0.001	0.12	1.125E-01	3.392E-02	3.426E 02	-8.361E-03
200.6	1.3125	12000.	660.	1.00	0.004	0.18	2.269E-01	7.296E-02	1.874E 01	-4.741E-01
200.6	1.3125	12000.	560.	1.00	0.003	0.20	2.120E-01	5.653E-02	5.971E 01	-1.351E-01
200.6	1.3125	12000.	660.	1.00	0.002	0.18	1.692E-01	5.088E-02	5.006E 02	-1.286E-02
200.6	1.3125	12000.	660.	1.00	0.001	0.14	1.125E-01	3.957E-02	1.948E 05	-1.995E-05
200.6	1.3125	12000.	660.	1.50	0.004	0.20	1.712E-01	8.107E-02	1.052E 02	-9.962E-02
200.6	1.3125	12000.	660.	1.50	0.003	0.22	2.120E-01	6.219E-02	5.648E 02	-1.702E-02
200.6	1.3125	12000.	660.	1.50	0.002	0.18	1.692E-01	5.088E-02	1.120E 04	-5.738E-04
200.6	1.3125	12000.	660.	1.50	0.001	0.14	1.125E-01	3.957E-02	8.601E 07	-4.519E-08
200.6	1.3125	12000.	660.	2.00	0.004	0.22	1.712E-01	8.917E-02	6.162E 02	-2.042E-02
200.6	1.3125	12000.	660.	2.00	0.003	0.22	2.120E-01	6.219E-02	4.669E 03	-2.056E-03
200.6	1.3125	12000.	660.	2.00	0.002	0.18	1.692E-01	5.088E-02	2.506E 05	-2.565E-05
200.6	1.3125	12000.	660.	2.00	0.001	0.14	1.125E-01	3.957E-02	3.797E 10	-1.024E-10

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
200.6	1.6250	7800.	660.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.080E 00	-2.415E 00
200.6	1.6250	7800.	660.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.134E 00	-1.437E 00
200.6	1.6250	7800.	660.	0.50	0.002	0.12	1.971E-01	4.864E-02	7.047E 00	-4.974E-01
200.6	1.6250	7800.	660.	0.50	0.001	0.12	1.125E-01	4.864E-02	1.094E 02	-2.775E-02
200.6	1.6250	7800.	660.	1.00	0.004	0.18	2.827E-01	7.296E-02	8.654E 00	-8.842E-01
200.6	1.6250	7800.	660.	1.00	0.003	0.18	2.120E-01	7.296E-02	2.278E 01	-3.107E-01
200.6	1.6250	7800.	660.	1.00	0.002	0.16	1.692E-01	6.485E-02	1.196E 02	-4.508E-02
200.6	1.6250	7800.	660.	1.00	0.001	0.16	1.125E-01	4.523E-02	1.626E 04	-2.513E-04
200.6	1.6250	7800.	660.	1.50	0.004	0.24	2.827E-01	6.784E-02	3.627E 01	-2.606E-01
200.6	1.6250	7800.	660.	1.50	0.003	0.22	2.538E-01	6.219E-02	1.289E 02	-6.041E-02
200.6	1.6250	7800.	660.	1.50	0.002	0.20	1.971E-01	5.653E-02	1.653E 03	-3.865E-03
200.6	1.6250	7800.	660.	1.50	0.001	0.16	1.125E-01	4.523E-02	2.073E 06	-1.971E-06
200.6	1.6250	7800.	660.	2.00	0.004	0.26	2.827E-01	7.349E-02	1.460E 02	-7.439E-02
200.6	1.6250	7800.	660.	2.00	0.003	0.24	2.538E-01	6.784E-02	8.024E 02	-1.147E-02
200.6	1.6250	7800.	660.	2.00	0.002	0.20	1.971E-01	5.653E-02	1.954E 04	-3.267E-04
200.6	1.6250	7800.	660.	2.00	0.001	0.16	1.125E-01	4.523E-02	2.644E 08	-1.545E-08
200.6	1.6250	12000.	660.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.126E 00	-2.365E 00
200.6	1.6250	12000.	660.	0.50	0.003	0.16	2.538E-01	6.485E-02	9.216E 00	-1.001E 00
200.6	1.6250	12000.	660.	0.50	0.002	0.18	1.971E-01	5.088E-02	3.849E 01	-2.122E-01
200.6	1.6250	12000.	660.	0.50	0.001	0.12	1.125E-01	4.864E-02	1.370E 03	-3.379E-03
200.6	1.6250	12000.	660.	1.00	0.004	0.24	2.827E-01	6.784E-02	3.977E 01	-3.648E-01
200.6	1.6250	12000.	660.	1.00	0.003	0.22	2.538E-01	6.219E-02	1.460E 02	-8.197E-02
200.6	1.6250	12000.	660.	1.00	0.002	0.20	1.971E-01	5.653E-02	1.999E 03	-4.917E-03
200.6	1.6250	12000.	660.	1.00	0.001	0.16	1.125E-01	4.523E-02	3.010E 06	-2.088E-06
200.6	1.6250	12000.	660.	1.50	0.004	0.26	2.827E-01	7.349E-02	3.144E 02	-5.297E-02
200.6	1.6250	12000.	660.	1.50	0.003	0.24	2.538E-01	6.784E-02	2.245E 03	-6.302E-03
200.6	1.6250	12000.	660.	1.50	0.002	0.20	1.971E-01	5.653E-02	8.935E 04	-1.099E-04
200.6	1.6250	12000.	660.	1.50	0.001	0.16	1.125E-01	4.523E-02	5.223E 09	-1.203E-09
200.6	1.6250	12000.	660.	2.00	0.004	0.28	2.827E-01	7.915E-02	2.570E 03	-7.493E-03
200.6	1.6250	12000.	660.	2.00	0.003	0.26	2.120E-01	7.349E-02	3.494E 04	-4.751E-04
200.6	1.6250	12000.	660.	2.00	0.002	0.22	1.692E-01	6.219E-02	5.128E 06	-2.317E-06
200.6	1.[illegible]250	12000.	660.	2.00	0.001	0.1[illegible]	1.125E-01	4.523E-02	9.062E 12	-6.936E-13

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
200.6	2.0000	7800.	660.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.080E 00	-2.971E 00
200.6	2.0000	7800.	660.	0.50	0.003	0.16	2.956E-01	6.485E-02	4.932E 00	-1.674E 00
200.6	2.0000	7800.	660.	0.50	0.002	0.16	1.971E-01	6.485E-02	1.564E 01	-4.436E-01
200.6	2.0000	7800.	660.	0.50	0.001	0.14	1.125E-01	5.675E-02	3.233E 02	-1.563E-02
200.6	2.0000	7800.	660.	1.00	0.004	0.22	2.827E-01	8.917E-02	1.673E 01	-7.910E-01
200.6	2.0000	7800.	660.	1.00	0.003	0.20	2.538E-01	8.107E-02	4.514E 01	-2.330E-01
200.6	2.0000	7800.	660.	1.00	0.002	0.22	2.249E-01	6.219E-02	4.003E 02	-2.381E-02
200.6	2.0000	7800.	660.	1.00	0.001	0.14	1.125E-01	5.675E-02	1.045E 05	-4.821E-05
200.6	2.0000	7800.	660.	1.50	0.004	0.28	3.384E-01	7.915E-02	8.908E 01	-1.748E-01
200.6	2.0000	7800.	660.	1.50	0.003	0.26	2.538E-01	7.349E-02	4.303E 02	-3.093E-02
200.6	2.0000	7800.	660.	1.50	0.002	0.22	2.249E-01	6.219E-02	8.008E 03	-1.187E-03
200.6	2.0000	7800.	660.	1.50	0.001	0.18	1.264E-01	5.088E-02	4.549E 07	-1.393E-07
200.6	2.0000	7800.	660.	2.00	0.004	0.30	2.827E-01	8.480E-02	4.676E 02	-3.789E-02
200.6	2.0000	7800.	660.	2.00	0.003	0.28	2.538E-01	7.915E-02	3.843E 03	-4.009E-03
200.6	2.0000	7800.	660.	2.00	0.002	0.24	1.971E-01	6.784E-02	2.017E 05	-5.610E-05
200.6	2.0000	7800.	660.	2.00	0.001	0.18	1.264E-01	5.088E-02	1.624E 10	-3.919E-10
200.6	2.0000	12000.	660.	0.50	0.004	0.20	3.384E-01	8.107E-02	7.529E 00	-2.423E 00
200.6	2.0000	12000.	660.	0.50	0.003	0.20	2.538E-01	8.107E-02	1.874E 01	-8.919E-01
200.6	2.0000	12000.	660.	0.50	0.002	0.18	1.971E-01	7.296E-02	8.995E 01	-1.441E-01
200.6	2.0000	12000.	660.	0.50	0.001	0.14	1.125E-01	5.675E-02	7.760E 03	-1.068E-03
200.6	2.0000	12000.	660.	1.00	0.004	0.28	3.384E-01	7.915E-02	9.994E 01	-2.394E-01
200.6	2.0000	12000.	660.	1.00	0.003	0.26	2.538E-01	7.349E-02	5.027E 02	-4.072E-02
200.6	2.0000	12000.	660.	1.00	0.002	0.24	1.971E-01	6.784E-02	1.204E 04	-1.446E-03
200.6	2.0000	12000.	660.	1.00	0.001	0.18	1.264E-01	5.088E-02	7.149E 07	-1.370E-07
200.6	2.0000	12000.	660.	1.50	0.004	0.30	2.827E-01	8.480E-02	1.204E 03	-2.261E-02
200.6	2.0000	12000.	660.	1.50	0.003	0.28	2.538E-01	7.915E-02	1.368E 04	-1.732E-03
200.6	2.0000	12000.	660.	1.50	0.002	0.24	1.971E-01	6.784E-02	1.321E 06	-1.318E-05
200.6	2.0000	12000.	660.	1.50	0.001	0.18	1.264E-01	5.088E-02	6.045E 11	-1.620E-11
200.6	2.0000	12000.	660.	2.00	0.004	0.30	2.827E-01	8.480E-02	1.281E 04	-2.124E-03
200.6	2.0000	12000.	660.	2.00	0.003	0.28	2.538E-01	7.915E-02	3.272E 05	-7.241E-05
200.6	2.0000	12000.	660.	2.00	0.002	0.24	1.971E-01	6.784E-02	1.449E 08	-1.201E-07
200.6	2.0000	12000.	660.	2.00	0.001	0.18	1.264E-01	5.088E-02	5.111E 15	-1.916E-15

PUMP UPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIU	LEAKAGE
200.6	1.3125	7800.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.074E 00	-2.564E 01
200.6	1.3125	7800.	760.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.125E 00	-1.528E 01
200.6	1.3125	7800.	760.	0.50	0.002	0.10	1.971E-01	4.053E-02	3.984E 00	-6.901E 00
200.6	1.3125	7800.	760.	0.50	0.001	0.10	1.125E-01	4.053E-02	3.222E 01	-6.596E-01
200.6	1.3125	7800.	760.	1.00	0.004	0.02	5.973E-02	4.000E-02	1.154E 00	-1.236E 01
200.6	1.3125	7800.	760.	1.00	0.003	0.14	2.120E-01	5.675E-02	8.615E 00	-5.300E 00
200.6	1.3125	7800.	760.	1.00	0.002	0.14	1.692E-01	5.675E-02	3.[illegible]56E 01	-1.135E 00
200.6	1.3125	7800.	760.	1.00	0.001	0.12	1.125E-01	3.392E-02	1.177E 03	-1.927E-02
200.6	1.3125	7800.	760.	1.50	0.004	0.20	2.827E-01	5.653E-02	1.360E 01	-4.996E 00
200.6	1.3125	7800.	760.	1.50	0.003	0.16	2.120E-01	6.485E-02	3.487E 01	-1.556E 00
200.6	1.3125	7800.	760.	1.50	0.002	0.18	1.692E-01	5.088E-02	2.836E 02	-1.804E-01
200.6	1.3125	7800.	760.	1.50	0.001	0.14	1.125E-01	3.957E-02	6.400E 04	-4.818E-04
200.6	1.3125	7800.	760.	2.00	0.004	0.22	2.827E-01	6.219E-02	3.994E 01	-1.955E 00
200.6	1.3125	7800.	760.	2.00	0.003	0.20	2.120E-01	5.653E-02	1.418E 02	-4.470E-01
200.6	1.3125	7800.	760.	2.00	0.002	0.18	1.692E-01	5.098E-02	1.863E 03	-2.737E-02
200.6	1.3125	7800.	760.	2.00	0.001	0.14	1.125E-01	3.957E-02	2.569E 06	-1.205E-05
200.6	1.3125	12000.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.[illegible]6E 00	-2.514E 01
200.6	1.3125	12000.	760.	0.50	0.003	0.12	2.538E-01	4.864E-02	4.170E 00	-1.437E 01
200.6	1.3125	12000.	760.	0.50	0.002	0.12	1.692E-01	4.864E-02	1.242E 01	-3.994E 00
200.6	1.3125	12000.	760.	0.50	0.001	0.12	1.125E-01	3.392E-02	2.302E 02	-1.521E-01
200.6	1.3125	12000.	760.	1.00	0.004	0.20	2.827E-01	5.653E-02	1.454E 01	-7.152E 00
200.6	1.3125	12000.	760.	1.00	0.003	0.16	2.120E-01	6.485E-02	3.019E 01	-2.181E 00
200.6	1.3125	12000.	760.	1.00	0.002	0.18	1.692E-01	5.088E-02	3.278E 02	-2.400E-01
200.6	1.3125	12000.	760.	1.00	0.001	0.14	1.125E-01	3.957E-02	8.500E 04	-5.581E-04
200.6	1.3125	12000.	760.	1.50	0.004	0.20	1.712E-01	8.107E-02	7.663E 01	-1.675E 00
200.6	1.3125	12000.	760.	1.50	0.003	0.20	2.120E-01	5.653E-02	3.039E 02	-3.197E-01
200.6	1.3125	12000.	760.	1.50	0.002	0.18	1.692E-01	5.088E-02	5.935E 03	-1.322E-02
200.6	1.3125	12000.	760.	1.50	0.001	0.14	1.125E-01	3.957E-02	[illegible].479E 07	-1.914E-06
200.6	1.3125	12000.	760.	2.00	0.004	0.22	1.712E-01	8.917E-02	3.9[illegible]8E 02	-3.864E-01
200.6	1.3125	12000.	760.	2.00	0.003	0.22	2.120E-01	6.219E-02	2.626E 03	-4.463E-02
200.6	1.3125	12000.	760.	2.00	0.002	0.18	1.692E-01	5.089E-02	1.074E 05	-7.299E-04
200.6	1.3125	12000.	760.	2.00	0.001	0.14	1.125E-01	3.957E-02	7.225E 09	-6.566E-09

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
200.6	1.6250	7800.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.074E 00	-3.172E 01
200.6	1.6250	7800.	760.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.125E 00	-1.890E 01
200.6	1.6250	7800.	760.	0.50	0.002	0.12	1.971E-01	4.864E-02	6.170E 00	-7.101E 00
200.6	1.6250	7800.	760.	0.50	0.001	0.12	1.125E-01	4.864E-02	7.945E 01	-4.679E-01
200.6	1.6250	7800.	760.	1.00	0.004	0.18	2.827E-01	7.296E-02	7.471E 00	-1.276E 01
200.6	1.6250	7800.	760.	1.00	0.003	0.18	2.120E-01	7.296E-02	1.841E 01	-4.744E 00
200.6	1.6250	7800.	760.	1.00	0.002	0.16	1.692E-01	6.485E-02	8.635E 01	-7.647E-01
200.6	1.6250	7800.	760.	1.00	0.001	0.12	1.125E-01	4.864E-02	6.312E 03	-5.817E-03
200.6	1.6250	7800.	760.	1.50	0.004	0.20	2.827E-01	8.107E-02	2.595E 01	-4.088E 00
200.6	1.6250	7800.	760.	1.50	0.003	0.22	2.538E-01	6.219E-02	9.257E 01	-1.030E 00
200.6	1.6250	7800.	760.	1.50	0.002	0.20	1.971E-01	5.653E-02	9.977E 02	-7.817E-02
200.6	1.6250	7800.	760.	1.50	0.001	0.16	1.125E-01	4.523E-02	7.693E 05	-6.477E-05
200.6	1.6250	7800.	760.	2.00	0.004	0.26	2.827E-01	7.349E-02	1.040E 02	-1.278E 00
200.6	1.6250	7800.	760.	2.00	0.003	0.24	2.538E-01	6.784E-02	5.088E 02	-2.209E-01
200.6	1.6250	7800.	760.	2.00	0.002	0.20	1.971E-01	5.653E-02	9.970E 03	-7.816E-03
200.6	1.6250	7800.	760.	2.00	0.001	0.16	1.125E-01	4.523E-02	7.056E 07	-7.067E-07
200.6	1.6250	12000.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.117E 00	-3.110E 01
200.6	1.6250	12000.	760.	0.50	0.003	0.16	2.538E-01	6.485E-02	7.922E 00	-1.450E 01
200.6	1.6250	12000.	760.	0.50	0.002	0.14	1.971E-01	5.675E-02	2.412E 01	-3.325E 00
200.6	1.6250	12000.	760.	0.50	0.001	0.12	1.125E-01	4.864E-02	8.380E 02	-6.748E-02
200.6	1.6250	12000.	760.	1.00	0.004	0.24	2.827E-01	6.784E-02	3.094E 01	-5.764E 00
200.6	1.6250	12000.	760.	1.00	0.003	0.22	2.538E-01	6.219E-02	1.040E 02	-1.409E 00
200.6	1.6250	12000.	760.	1.00	0.002	0.20	1.971E-01	5.653E-02	1.191E 03	-1.007E-01
200.6	1.6250	12000.	760.	1.00	0.001	0.16	1.125E-01	4.523E-02	1.090E 06	-7.039E-05
200.6	1.6250	12000.	760.	1.50	0.004	0.26	2.827E-01	7.349E-02	2.125E 02	-9.578E-01
200.6	1.6250	12000.	760.	1.50	0.003	0.24	2.538E-01	6.784E-02	1.327E 03	-1.301E-01
200.6	1.6250	12000.	760.	1.50	0.002	0.20	1.971E-01	5.653E-02	4.110E 04	-2.916E-03
200.6	1.6250	12000.	760.	1.50	0.001	0.16	1.125E-01	4.523E-02	1.138E 09	-6.743E-08
200.6	1.6250	12000.	760.	2.00	0.004	0.28	2.827E-01	7.915E-02	1.506E 03	-1.561E-01
200.6	1.6250	12000.	760.	2.00	0.003	0.26	2.120E-01	7.349E-02	1.713E 04	-1.182E-02
200.6	1.6250	12000.	760.	2.00	0.002	0.22	1.692E-01	6.219E-02	1.790E 06	-8.101E-05
200.6	1.6250	12000.	760.	2.00	0.001	0.16	1.125E-01	4.523E-02	1.188E 12	-6.459E-11

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
200.6	2.0000	7800.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.374E 00	-3.901E 01
200.6	2.0000	7800.	760.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.125E 00	-2.324E 01
200.6	2.0000	7800.	760.	0.50	0.002	0.16	1.971E-01	6.485E-02	1.297E 01	-6.713E 00
200.6	2.0000	7800.	760.	0.50	0.001	0.14	1.125E-01	5.675E-02	2.181E 02	-2.833E-01
200.6	2.0000	7800.	760.	1.00	0.004	0.22	2.827E-01	8.917E-02	1.381E 01	-1.166E 01
200.6	2.0000	7800.	760.	1.00	0.003	0.20	2.538E-01	8.107E-02	3.482E 01	-3.711E 00
200.6	2.0000	7800.	760.	1.00	0.002	0.22	2.249E-01	6.219E-02	2.661E 02	-4.376E-01
200.6	2.0000	7800.	760.	1.00	0.001	0.14	1.125E-01	5.675E-02	4.757E 04	-1.293E-03
200.6	2.0000	7800.	760.	1.50	0.004	0.28	3.384E-01	7.916E-02	6.561E 01	-2.909E 00
200.6	2.0000	7800.	760.	1.50	0.003	0.26	2.538E-01	7.349E-02	2.847E 02	-5.713E-01
200.6	2.0000	7800.	760.	1.50	0.002	0.22	2.249E-01	6.210E-02	4.342E 03	-2.673E-02
200.6	2.0000	7800.	760.	1.50	0.001	0.18	1.264E-01	5.088E-02	1.369E 07	-5.675E-06
200.6	2.0000	7800.	760.	2.00	0.004	0.30	2.827E-01	8.480E-02	3.076E 02	-7.037E-01
200.6	2.0000	7800.	760.	2.00	0.003	0.28	2.538E-01	7.915E-02	2.190E 03	-8.585E-02
200.6	2.0000	7800.	760.	2.00	0.002	0.24	1.971E-01	6.784E-02	8.777E 04	-1.573E-03
200.6	2.0000	7800.	760.	2.00	0.001	0.18	1.264E-01	5.088E-02	3.274E 09	-2.372E-08
200.6	2.0000	12000.	760.	0.50	0.004	0.18	3.384E-01	7.296E-02	5.513E 00	-3.466E 01
200.6	2.0000	12000.	760.	0.50	0.003	0.18	2.538E-01	7.276E-02	1.263E 01	-1.338E 01
200.6	2.0000	12000.	760.	0.50	0.002	0.20	2.249E-01	5.653E-02	6.261E 01	-2.374E 00
200.6	2.0000	12000.	760.	0.50	0.001	0.14	1.125E-01	5.675E-02	3.962E 03	-2.388E-02
200.6	2.0000	12000.	760.	1.00	0.004	0.28	3.384E-01	7.915E-02	7.304E 01	-4.014E 00
200.6	2.0000	12000.	760.	1.00	0.003	0.26	2.538E-01	7.349E-02	3.291E 02	-7.600E-01
200.6	2.0000	12000.	760.	1.00	0.002	0.22	2.249E-01	6.219E-02	5.382E 03	-3.318E-02
200.6	2.0000	12000.	760.	1.00	0.001	0.18	1.264E-01	5.088E-02	2.086E 07	-5.729E-06
200.6	2.0000	12000.	760.	1.50	0.004	0.30	2.827E-01	9.480E-02	7.427E 02	-4.476E-01
200.6	2.0000	12000.	760.	1.50	0.003	0.28	2.538E-01	7.915E-02	7.152E 03	-4.044E-02
200.6	2.0000	12000.	760.	1.50	0.002	0.24	1.971E-01	6.784E-02	5.057E 05	-4.201E-04
200.6	2.0000	12000.	760.	1.50	0.001	0.18	1.264E-01	5.088E-02	9.527E 10	-1.254E-09
200.6	2.0000	12000.	760.	2.00	0.004	0.30	2.827E-01	8.480E-02	6.726E 03	-4.936E-02
200.6	2.0000	12000.	760.	2.00	0.003	0.28	2.538E-01	7.915E-02	1.373E 05	-2.099E-03
200.6	2.0000	12000.	760.	2.00	0.002	0.24	1.971E-01	6.784E-02	4.029E 07	-5.273E-06
200.6	2.0000	12000.	760.	2.00	0.001	0.18	1.264E-01	5.088E-02	4.351E 14	-2.746E-13

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
200.6	1.3125	7800.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.070E 00	-1.788E 02
200.6	1.3125	7800.	860.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.117E 00	-1.067E 02
200.6	1.3125	7800.	860.	0.50	0.002	0.08	1.692E-01	4.224E-02	3.052E 00	-5.035E 01
200.6	1.3125	7800.	860.	0.50	0.001	0.10	1.125E-01	4.053E-02	2.616E 01	-5.354E 00
200.6	1.3125	7800.	860.	1.00	0.004	0.02	5.973E-02	4.000E-02	1.144E 00	-8.641E 01
200.6	1.3125	7800.	860.	1.00	0.003	0.14	2.120E-01	5.675E-02	7.571E 00	-4.018E 01
200.6	1.3125	7800.	860.	1.00	0.002	0.14	1.692E-01	5.675E-02	2.947E 01	-9.276E 00
200.6	1.3125	7800.	860.	1.00	0.001	0.12	1.125E-01	3.392E-02	7.704E 02	-1.927E-01
200.6	1.3125	7800.	860.	1.50	0.004	0.16	2.827E-01	6.485E-02	9.937E 00	-3.859E 01
200.6	1.3125	7800.	860.	1.50	0.003	0.16	2.120E-01	6.485E-02	2.818E 01	-1.269E 01
200.6	1.3125	7800.	860.	1.50	0.002	0.18	1.692E-01	5.088E-02	2.022E 02	-1.658E 00
200.6	1.3125	7800.	860.	1.50	0.001	0.14	1.125E-01	3.957E-02	3.297E 04	-6.120E-03
200.6	1.3125	7800.	860.	2.00	0.004	0.22	2.827E-01	6.219E-02	3.202E 01	-1.606E 01
200.6	1.3125	7800.	860.	2.00	0.003	0.20	2.120E-01	5.653E-02	1.054E 02	-3.945E 00
200.6	1.3125	7800.	860.	2.00	0.002	0.18	1.692E-01	5.088E-02	1.186E 03	-2.813E-01
200.6	1.3125	7800.	860.	2.00	0.001	0.14	1.125E-01	3.957E-02	1.057E 06	-1.908E-04
200.6	1.3125	12000.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.109E 00	-1.756E 02
200.6	1.3125	12000.	860.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.185E 00	-1.035E 02
200.6	1.3125	12000.	860.	0.50	0.002	0.12	1.692E-01	4.864E-02	1.068E 01	-3.083E 01
200.6	1.3125	12000.	860.	0.50	0.001	0.10	1.125E-01	4.053E-02	1.517E 02	-1.375E 00
200.6	1.3125	12000.	860.	1.00	0.004	0.16	2.827E-01	6.485E-02	1.054E 01	-5.562E 01
200.6	1.3125	12000.	860.	1.00	0.003	0.16	2.120E-01	6.485E-02	3.070E 01	-1.787E 01
200.6	1.3125	12000.	860.	1.00	0.002	0.18	1.692E-01	5.088E-02	2.316E 02	-2.225E 00
200.6	1.3125	12000.	860.	1.00	0.001	0.14	1.125E-01	3.957E-02	4.305E 04	-7.210E-03
200.6	1.3125	12000.	860.	1.50	0.004	0.20	1.712E-01	8.107E-02	5.908E 01	-1.427E 01
200.6	1.3125	12000.	860.	1.50	0.003	0.20	2.120E-01	5.653E-02	2.157E 02	-2.950E 00
200.6	1.3125	12000.	860.	1.50	0.002	0.18	1.692E-01	5.088E-02	3.526E 03	-1.456E-01
200.6	1.3125	12000.	860.	1.50	0.001	0.14	1.125E-01	3.957E-02	8.932E 06	-3.475E-05
200.6	1.3125	12000.	860.	2.00	0.004	0.20	1.712E-01	8.107E-02	2.301E 02	-3.619E 00
200.6	1.3125	12000.	860.	2.00	0.003	0.22	2.120E-01	6.219E-02	1.638E 03	-4.682E-01
200.6	1.3125	12000.	860.	2.00	0.002	0.18	1.692E-01	5.088E-02	5.366E 04	-9.563E-03
200.6	1.3125	12000.	860.	2.00	0.001	0.14	1.125E-01	3.957E-02	1.853E 09	-1.675E-07

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
200.6	1.6250	7800.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.070E 00	-2.212E 02
200.6	1.6250	7800.	860.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.117E 00	-1.320E 02
200.6	1.6250	7800.	860.	0.50	0.002	0.12	1.971E-01	4.864E-02	5.532E 00	-5.300E 01
200.6	1.6250	7800.	860.	0.50	0.001	0.12	1.125E-01	4.864E-02	6.112E 01	-3.995E 00
200.6	1.6250	7800.	860.	1.00	0.004	0.18	2.827E-01	7.296E-02	6.623E 00	-9.612E 01
200.6	1.6250	7800.	860.	1.00	0.003	0.16	2.538E-01	6.485E-02	1.255E 01	-3.699E 01
200.6	1.6250	7800.	860.	1.00	0.002	0.16	1.692E-01	6.485E-02	6.610E 01	-6.559E 00
200.6	1.6250	7800.	860.	1.00	0.001	0.12	1.125E-01	4.864E-02	3.736E 03	-6.431E-02
200.6	1.6250	7800.	860.	1.50	0.004	0.20	2.827E-01	8.107E-02	2.135E 01	-3.279E 01
200.6	1.6250	7800.	860.	1.50	0.003	0.22	2.538E-01	6.219E-02	7.057E 01	-8.867E 00
200.6	1.6250	7800.	860.	1.50	0.002	0.20	1.971E-01	5.653E-02	6.596E 02	-7.741E-01
200.6	1.6250	7800.	860.	1.50	0.001	0.16	1.125E-01	4.523E-02	3.417E 05	-9.549E-04
200.6	1.6250	7800.	860.	2.00	0.004	0.26	2.827E-01	7.349E-02	7.873E 01	-1.108E 01
200.6	1.6250	7800.	860.	2.00	0.003	0.24	2.538E-01	6.784E-02	3.502E 02	-2.102E 00
200.6	1.6250	7800.	860.	2.00	0.002	0.20	1.971E-01	5.653E-02	5.741E 03	-8.881E-02
200.6	1.6250	7800.	860.	2.00	0.001	0.16	1.125E-01	4.523E-02	2.389E 07	-1.366E-05
200.6	1.6250	12000.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.109E 00	-2.172E 02
200.6	1.6250	12000.	860.	0.50	0.003	0.14	2.538E-01	5.675E-02	5.596E 00	-1.094E 02
200.6	1.6250	12000.	860.	0.50	0.002	0.14	1.971E-01	5.675E-02	1.993E 01	-2.657E 01
200.6	1.6250	12000.	860.	0.50	0.001	0.12	1.125E-01	4.864 -02	5.598E 02	-6.613E-01
200.6	1.6250	12000.	860.	1.00	0.004	0.20	2.827E-01	8.107E-02	2.309E 01	-4.647E 01
200.6	1.6250	12000.	860.	1.00	0.003	0.22	2.538E-01	6.219E-02	7.870E 01	-1.221E 01
200.6	1.6250	12000.	860.	1.00	0.002	0.20	1.971E-01	5.653E-02	7.790E 02	-1.008E 00
200.6	1.6250	12000.	860.	1.00	0.001	0.16	1.125E-01	4.523E-02	4.737E 05	-1.060E-03
200.6	1.6250	12000.	860.	1.50	0.004	0.26	2.827E-01	7.349E-02	1.541E 02	-8.656E 00
200.6	1.6250	12000.	860.	1.50	0.003	0.24	2.538E-01	6.784E-02	8.626E 02	-1.311E 00
200.6	1.6250	12000.	860.	1.50	0.002	0.20	1.971E-01	5.653E-02	2.174E 04	-3.607E-02
200.6	1.6250	12000.	860.	1.50	0.001	0.16	1.125E-01	4.523E-02	3.260E 08	-1.540E-06
200.6	1.6250	12000.	860.	2.00	0.004	0.28	2.827E-01	7.915E-02	9.711E 02	-1.585E 00
200.6	1.6250	12000.	860.	2.00	0.003	0.24	2.538E-01	6.784E-02	8.211E 03	-1.376E-01
200.6	1.6250	12000.	860.	2.00	0.002	0.22	1.692E-01	6.219E-02	7.554E 05	-1.256E-03
200.6	1.6250	12000.	860.	2.00	0.001	0.16	1.125E-01	4.523E-02	2.244E 11	-2.237E-09

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
200.6	2.0000	7800.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.070E 00	-2.721E 02
200.6	2.0000	7800.	860.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.117E 00	-1.623E 02
200.6	2.0000	7800.	860.	0.50	0.002	0.14	2.249E-01	5.675E-02	8.793E 00	-5.164E 01
200.6	2.0000	7800.	860.	0.50	0.001	0.14	1.125E-01	5.675E-02	1.579E 02	-2.564E 00
200.6	2.0000	7800.	860.	1.00	0.004	0.20	3.384E-01	8.107E-02	9.964E 00	-9.161E 01
200.6	2.0000	7800.	860.	1.00	0.003	0.20	2.538E-01	8.107E-02	2.815E 01	-3.025E 01
200.6	2.0000	7800.	860.	1.00	0.002	0.18	1.971E-01	7.296E-02	1.680E 02	-3.983E 00
200.6	2.0000	7800.	860.	1.00	0.001	0.14	1.125E-01	5.675E-02	2.495E 04	-1.613E-02
200.6	2.0000	7800.	860.	1.50	0.004	0.28	3.384E-01	7.915E-02	5.106E 01	-2.457E 01
200.6	2.0000	7800.	860.	1.50	0.003	0.26	2.538E-01	7.349E-02	2.029E 02	-5.252E 00
200.6	2.0000	7800.	860.	1.50	0.002	0.22	2.249E-01	6.219E-02	2.628E 03	-2.890E-01
200.6	2.0000	7800.	860.	1.50	0.001	0.18	1.264E-01	5.088E-02	5.112E 06	-9.941E-05
200.6	2.0000	7800.	860.	2.00	0.004	0.30	2.827E-01	8.480E-02	2.182E 02	-6.499E 00
200.6	2.0000	7800.	860.	2.00	0.003	0.26	2.538E-01	7.349E-02	1.192E 03	-8.902E-01
200.6	2.0000	7800.	860.	2.00	0.002	0.24	1.971E-01	6.784E-02	4.437E 04	-2.036E-02
200.6	2.0000	7800.	860.	2.00	0.001	0.18	1.264E-01	5.088E-02	8.806E 08	-5.771E-07
200.6	2.0000	12000.	860.	0.50	0.004	0.18	3.384E-01	7.296E-02	4.977E 00	-2.573E 02
200.6	2.0000	12000.	860.	0.50	0.003	0.18	2.538E-01	7.296E-02	1.090E 01	-1.034E 02
200.6	2.0000	12000.	860.	0.50	0.002	0.20	2.249E-01	5.653E-02	4.886E 01	-2.017E 01
200.5	2.0000	12000.	860.	0.50	0.001	0.14	1.125E-01	5.675E-02	2.412E 03	-2.568E-01
200.6	2.0000	12000.	860.	1.00	0.004	0.28	3.384E-01	7.915E-02	5.648E 01	-3.410E 01
200.6	2.0000	12000.	860.	1.00	0.003	0.26	2.538E-01	7.349E-02	2.325E 02	-7.047E 00
200.6	2.0000	12000.	860.	1.00	0.002	0.22	2.249E-01	6.219E-02	3.216E 03	-3.633E-01
200.6	2.0000	12000.	860.	1.00	0.001	0.18	1.264E-01	5.088E-02	7.597E 06	-1.029E-04
200.6	2.0000	12000.	860.	1.50	0.004	0.30	2.827E-01	8.480E-02	4.997E 02	-4.355E 00
200.6	2.0000	12000.	860.	1.50	0.003	0.28	2.538E-01	7.915E-02	4.201E 03	-4.504E-01
200.6	2.0000	12000.	860.	1.50	0.002	0.24	1.971E-01	6.784E-02	2.301E 05	-6.040E-03
200.6	2.0000	12000.	860.	1.50	0.001	0.18	1.264E-01	5.088E-02	2.094E 10	-3.734E-08
200.6	2.0000	12000.	860.	2.00	0.004	0.30	2.827E-01	8.480E-02	3.966E 03	-5.478E-01
200.6	2.0000	12000.	860.	2.00	0.003	0.28	2.538E-01	7.915E-02	6.779E 04	-2.791E-02
200.6	2.0000	12000.	860.	2.00	0.002	0.24	1.971E-01	6.784E-02	1.410E 07	-9.855E-05
200.6	2.0000	12000.	860.	2.00	0.001	0.18	1.264E-01	5.088E-02	5.771E 13	-1.355E-11

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	1.3125	7800.	660.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.107E 00	-5.329E-03
354.0	1.3125	7800.	660.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.182E 00	-3.144E-03
354.0	1.3125	7800.	660.	0.50	0.002	0.12	1.692E-01	4.864E-02	1.032E 01	-9.568E-04
354.0	1.3125	7800.	660.	0.50	0.001	0.10	1.125E-01	4.053E-02	1.412E 02	-4.420E-05
354.0	1.3125	7800.	660.	1.00	0.004	0.16	2.827E-01	6.485E-02	1.019E 01	-1.726E-03
354.0	1.3125	7800.	660.	1.00	0.003	0.16	2.120E-01	6.485E-02	2.923E 01	-5.619E-04
354.0	1.3125	7800.	660.	1.00	0.002	0.18	1.692E-01	5.088E-02	2.142E 02	-7.193E-05
354.0	1.3125	7800.	660.	1.00	0.001	0.14	1.125E-01	3.957E-02	3.694E 04	-2.512E-07
354.0	1.3125	7800.	660.	1.50	0.004	0.20	1.712E-01	8.107E-02	5.572E 01	-4.529E-04
354.0	1.3125	7800.	660.	1.50	0.003	0.20	2.120E-01	5.653E-02	1.997E 02	-9.529E-05
354.0	1.3125	7800.	660.	1.50	0.002	0.18	1.692E-01	5.088E-02	3.136E 03	-4.893E-06
354.0	1.3125	7800.	660.	1.50	0.001	0.14	1.125E-01	3.957E-02	7.100E 06	-1.307E-09
354.0	1.3125	7800.	660.	2.00	0.004	0.20	1.712E-01	8.107E-02	2.128E 02	-1.170E-04
354.0	1.3125	7800.	660.	2.00	0.003	0.22	2.120E-01	6.219E-02	1.473E 03	-1.556E-05
354.0	1.3125	7800.	660.	2.00	0.002	0.18	1.692E-01	5.088E-02	4.590E 04	-3.342E-07
354.0	1.3125	7800.	660.	2.00	0.001	0.14	1.125E-01	3.957E-02	1.365E 09	-6.799E-12
354.0	1.3125	12000.	660.	0.50	0.004	0.14	2.827E-01	5.675E-02	4.826E 00	-4.883E-03
354.0	1.3125	12000.	660.	0.50	0.003	0.14	2.120E-01	5.675E-02	1.061E 01	-1.945E-03
354.0	1.3125	12000.	660.	0.50	0.002	0.14	1.692E-01	5.675E-02	5.175E 01	-3.681E-04
354.0	1.3125	12000.	660.	0.50	0.001	0.14	1.125E-01	3.957E-02	3.262E 03	-4.378E-06
354.0	1.3125	12000.	660.	1.00	0.004	0.20	1.712E-01	8.107E-02	6.177E 01	-6.274E-04
354.0	1.3125	12000.	660.	1.00	0.003	0.20	2.120E-01	5.653E-02	2.288E 02	-1.279E-04
354.0	1.3125	12000.	660.	1.00	0.002	0.18	1.692E-01	5.088E-02	3.855E 03	-6.123E-06
354.0	1.3125	12000.	660.	1.00	0.001	0.14	1.125E-01	3.957E-02	1.064E 07	-1.342E-09
354.0	1.3125	12000.	660.	1.50	0.004	0.22	1.712E-01	8.917E-02	6.018E 02	-7.680E-05
354.0	1.3125	12000.	660.	1.50	0.003	0.22	2.120E-01	6.219E-02	4.526E 03	-7.790E-06
354.0	1.3125	12000.	660.	1.50	0.002	0.18	1.692E-01	5.088E-02	2.393E 05	-9.859E-08
354.0	1.3125	12000.	660.	1.50	0.001	0.14	1.125E-01	3.957E-02	3.471E 10	-4.113E-13
354.0	1.3125	12000.	660.	2.00	0.004	0.22	1.712E-01	8.917E-02	5.080E 03	-9.083E-06
354.0	1.3125	12000.	660.	2.00	0.003	0.22	2.120E-01	6.219E-02	7.487E 04	-4.709E-07
354.0	1.3125	12000.	660.	2.00	0.002	0.20	1.692E-01	5.653E-02	1.846E 07	-1.578E-09
354.0	1.3125	12000.	660.	2.00	0.001	0.14	1.125E-01	3.957E-02	1.132E 14	-1.261E-16

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	1.6250	7800.	660.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.108E 00	-6.592E-03
354.0	1.6250	7800.	660.	0.50	0.003	0.14	2.538E-01	5.675E-02	5.459E 00	-3.372E-03
354.0	1.6250	7800.	660.	0.50	0.002	0.14	1.971E-01	5.675E-02	1.910E 01	-5.309E-04
354.0	1.6250	7800.	660.	0.50	0.001	0.12	1.125E-01	4.864E-02	5.112E 02	-2.165E-05
354.0	1.6250	7800.	660.	1.00	0.004	0.20	2.827E-01	8.107E-02	2.207E 01	-1.456E-03
354.0	1.6250	7800.	660.	1.00	0.003	0.22	2.538E-01	6.219E-02	7.393E 01	-3.890E-04
354.0	1.6250	7800.	660.	1.00	0.002	0.20	1.971E-01	5.653E-02	7.081E 02	-3.316E-05
354.0	1.6250	7800.	660.	1.00	0.001	0.16	1.125E-01	4.523E-02	3.928E 05	-3.820E-08
354.0	1.6250	7800.	660.	1.50	0.004	0.26	2.827E-01	7.349E-02	1.434E 02	-2.783E-04
354.0	1.6250	7800.	660.	1.50	0.003	0.24	2.538E-01	6.784E-02	7.829E 02	-4.318E-05
354.0	1.6250	7800.	660.	1.50	0.002	0.20	1.971E-01	5.653E-02	1.884E 04	-1.244E-06
354.0	1.6250	7800.	660.	1.50	0.001	0.16	1.125E-01	4.523E-02	2.461E 08	-6.096E-11
354.0	1.6250	7800.	660.	2.00	0.004	0.28	2.827E-01	7.915E-02	8.799E 02	-5.229E-05
354.0	1.6250	7800.	660.	2.00	0.003	0.24	2.538E-01	6.784E-02	7.215E 03	-4.680E-06
354.0	1.6250	7800.	660.	2.00	0.002	0.22	1.692E-01	6.219E-02	6.221E 05	-4.560E-08
354.0	1.6250	7800.	660.	2.00	0.001	0.16	1.125E-01	4.523E-02	1.543E 11	-9.727E-14
354.0	1.6250	12000.	660.	0.50	0.004	0.18	2.827E-01	7.296E-02	9.072E 00	-4.737E-03
354.0	1.6250	12000.	660.	0.50	0.003	0.18	2.120E-01	7.296E-02	2.439E 01	-1.635E-03
354.0	1.6250	12000.	660.	0.50	0.002	0.16	1.692E-01	6.485E-02	1.328E 02	-2.292E-04
354.0	1.6250	12000.	660.	0.50	0.001	0.16	1.125E-01	4.523E-02	2.010E 04	-1.149E-06
354.0	1.6250	12000.	660.	1.00	0.004	0.26	2.827E-01	7.349E-02	1.628E 02	-3.766E-04
354.0	1.6250	12000.	660.	1.00	0.003	0.24	2.538E-01	6.784E-02	9.287E 02	-5.599E-05
354.0	1.6250	12000.	660.	1.00	0.002	0.20	1.971E-01	5.653E-02	2.425E 04	-1.487E-06
354.0	1.6250	12000.	660.	1.00	0.001	0.16	1.125E-01	4.523E-02	4.040E 08	-5.714E-11
354.0	1.6250	12000.	660.	1.50	0.004	0.28	2.827E-01	7.915E-02	2.497E 03	-2.832E-05
354.0	1.6250	12000.	660.	1.50	0.003	0.26	2.120E-01	7.349E-02	3.362E 04	-1.813E-06
354.0	1.6250	12000.	660.	1.50	0.002	0.22	1.692E-01	6.219E-02	4.844E 06	-9.009E-09
354.0	1.6250	12000.	660.	1.50	0.001	0.16	1.125E-01	4.523E-02	8.119E 12	-2.843E-15
354.0	1.6250	12000.	660.	2.00	0.004	0.28	2.827E-01	7.915E-02	3.387E 04	-2.087E-06
354.0	1.6250	12000.	660.	2.00	0.003	0.26	2.120E-01	7.349E-02	1.085E 06	-5.618E-08
354.0	1.6250	12000.	660.	2.00	0.002	0.22	1.692E-01	6.219E-02	8.197E 09	-5.324E-11
354.0	1.6250	12000.	660.	2.00	0.001	0.16	1.125E-01	4.523E-02	1.632E 17	-1.415E-19

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	2.0000	7800.	660.	0.50	0.004	0.18	3.384E-01	7.296E-02	4.863E 00	-7.918E-03
354.0	2.0000	7800.	660.	0.50	0.003	0.18	2.538E-01	7.296E-02	1.053E 01	-3.210E-03
354.0	2.0000	7800.	660.	0.50	0.002	0.20	2.249E-01	5.653E-02	4.621E 01	-6.382E-04
354.0	2.0000	7800.	660.	0.50	0.001	0.14	1.125E-01	5.675E-02	2.157E 03	-8.584E-06
354.0	2.0000	7800.	660.	1.00	0.004	0.28	3.384E-01	7.915E-02	5.330E 01	-1.081E-03
354.0	2.0000	7800.	660.	1.00	0.003	0.26	2.538E-01	7.349E-02	2.150E 02	-2.279E-04
354.0	2.0000	7800.	660.	1.00	0.002	0.22	2.249E-01	6.219E-02	2.864E 03	-1.219E-05
354.0	2.0000	7800.	660.	1.00	0.001	0.18	1.264E-01	5.088E-02	6.053E 06	-3.862E-09
354.0	2.0000	7800.	660.	1.50	0.004	0.30	2.827E-01	8.480E-02	4.571E 02	-1.423E-04
354.0	2.0000	7800.	660.	1.50	0.003	0.28	2.538E-01	7.915E-02	3.728E 03	-1.518E-05
354.0	2.0000	7800.	660.	1.50	0.002	0.24	1.971E-01	6.784E-02	1.928E 05	-2.155E-07
354.0	2.0000	7800.	660.	1.50	0.001	0.18	1.264E-01	5.088E-02	1.489E 10	-1.570E-12
354.0	2.0000	7800.	660.	2.00	0.004	0.30	2.827E-01	8.480E-02	3.521E 03	-1.844E-05
354.0	2.0000	7800.	660.	2.00	0.003	0.28	2.538E-01	7.915E-02	5.770E 04	-9.786E-07
354.0	2.0000	7800.	660.	2.00	0.002	0.24	1.971E-01	6.784E-02	[illegible]	-3.730E-09
354.0	2.0000	7800.	660.	2.00	0.001	0.18	1.264E-01	5.088E-02	3.663E 13	-6.380E-16
354.0	2.0000	12000.	660.	0.50	0.004	0.22	2.827E-01	8.917E-02	1.779E 01	-4.186E-03
354.0	2.0000	12000.	660.	0.50	0.003	0.24	2.956E-01	6.784E-02	5.393E 01	-1.208E-03
354.0	2.0000	12000.	660.	0.50	0.002	0.22	2.249E-01	6.219E-02	4.563E 02	-1.180E-04
354.0	2.0000	12000.	660.	0.50	0.001	0.14	1.125E-01	5.675E-02	1.346E 05	-2.116E-07
354.0	2.0000	12000.	660.	1.00	0.004	0.30	2.827E-01	8.480E-02	5.349E 02	-1.871E-04
354.0	2.0000	12000.	660.	1.00	0.003	0.28	2.538E-01	7.915E-02	4.603E 03	-1.891E-05
354.0	2.0000	12000.	660.	1.00	0.002	0.24	1.971E-01	6.784E-02	2.634E 05	-2.427E-07
354.0	2.0000	12000.	660.	1.00	0.001	0.18	1.264E-01	5.088E-02	2.715E 10	-1.324E-12
354.0	2.0000	12000.	660.	1.50	0.004	0.30	2.827E-01	8.480E-02	1.237E 04	-8.075E-06
354.0	2.0000	12000.	660.	1.50	0.003	0.28	2.538E-01	7.915E-02	3.122E 05	-2.787E-07
354.0	2.0000	12000.	660.	1.50	0.002	0.24	1.971E-01	6.784E-02	1.352E 08	-4.729E-10
354.0	2.0000	12000.	660.	1.50	0.001	0.18	1.264E-01	5.088E-02	4.473E 15	-8.038E-18
354.0	2.0000	12000.	660.	2.00	0.004	0.30	2.827E-01	8.480E-02	2.861E 05	-3.492E-07
354.0	2.0000	12000.	660.	2.00	0.003	0.28	2.538E-01	7.915E-02	2.118E 07	-4.107E-09
354.0	2.0000	12000.	660.	2.00	0.002	0.24	1.971E-01	6.784E-02	6.938E 10	-9.213E-13
354.0	2.0000	12000.	660.	2.00	0.001	0.18	1.264E-01	5.086E-02	7.371E 20	-4.878E-23

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	1.3125	7800.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.100E 00	-2.227E-01
354.0	1.3125	7800.	760.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.169E 00	-1.317E-01
354.0	1.3125	7800.	760.	0.50	0.002	0.12	1.692E-01	4.864E-02	8.807E 00	-4.434E-02
354.0	1.3125	7800.	760.	0.50	0.001	0.10	1.125E-01	4.053E-02	1.008E 02	-2.409E-03
354.0	1.3125	7800.	760.	1.00	0.004	0.16	2.827E-01	6.485E-02	8.690E 00	-7.993E-02
354.0	1.3125	7800.	760.	1.00	0.003	0.16	2.120E-01	6.485E-02	2.323E 01	-2.769E-02
354.0	1.3125	7800.	760.	1.00	0.002	0.14	1.692E-01	5.675E-02	1.192E 02	-3.985E-03
354.0	1.3125	7800.	760.	1.00	0.001	0.14	1.125E-01	3.957E-02	1.805E 04	-1.995E-05
354.0	1.3125	7800.	760.	1.50	0.004	0.22	2.827E-01	6.219E-02	3.940E 01	-2.315E-02
354.0	1.3125	7800.	760.	1.50	0.003	0.20	2.120E-01	5.653E-02	1.392E 02	-5.315E-03
354.0	1.3125	7800.	760.	1.50	0.002	0.18	1.692E-01	5.088E-02	1.812E 03	-3.285E-04
354.0	1.3125	7800.	760.	1.50	0.001	0.14	1.125E-01	3.957E-02	2.425E 06	-1.485E-07
354.0	1.3125	7800.	760.	2.00	0.004	0.20	1.712E-01	8.107E-02	1.477E 02	-6.553E-03
354.0	1.3125	7800.	760.	2.00	0.003	0.22	2.120E-01	6.219E-02	8.964E 02	-9.928E-04
354.0	1.3125	7800.	760.	2.00	0.002	0.18	1.692E-01	5.088E-02	2.210E 04	-2.693E-05
354.0	1.3125	7800.	760.	2.00	0.001	0.14	1.125E-01	3.957E-02	3.257E 08	-1.105E-09
354.0	1.3125	12000.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.158E 00	-2.169E-01
354.0	1.3125	12000.	760.	0.50	0.003	0.14	2.120E-01	5.675E-02	9.030E 00	-9.027E-02
354.0	1.3125	12000.	760.	0.50	0.002	0.14	1.692E-01	5.675E-02	3.956E 01	-1.880E-02
354.0	1.3125	12000.	760.	0.50	0.001	0.14	1.125E-01	3.957E-02	1.880E 03	-2.947E-04
354.0	1.3125	12000.	760.	1.00	0.004	0.22	2.827E-01	6.219E-02	4.329E 01	-[illegible].234E-02
354.0	1.3125	12000.	760.	1.00	0.003	0.20	2.120E-01	5.653E-02	1.580E 02	-7.198E-03
354.0	1.3125	12000.	760.	1.00	0.002	0.18	1.692E-01	5.088E-02	2.197E 03	-4.170E-04
354.0	1.3125	12000.	760.	1.00	0.001	0.14	1.125E-01	3.957E-02	3.535E 06	-1.567E-07
354.0	1.3125	12000.	760.	1.50	0.004	0.22	1.712E-01	8.917E-02	3.692E 02	-4.611E-03
354.0	1.3125	12000.	760.	1.50	0.003	0.22	2.120E-01	6.219E-02	2.551E 03	-5.363E-04
354.0	1.3125	12000.	760.	1.50	0.002	0.18	1.692E-01	5.088E-02	1.030E 05	-8.892E-06
354.0	1.3125	12000.	760.	1.50	0.001	0.14	1.125E-01	3.957E-02	6.646E 09	-8.334E-11
354.0	1.3125	12000.	760.	2.00	0.004	0.22	1.712E-01	8.917E-02	2.841E 03	-6.302E-04
354.0	1.3125	12000.	760.	2.00	0.003	0.22	2.120E-01	6.219E-02	3.486E 04	-3.924E-05
354.0	1.3125	12000.	760.	2.00	0.002	0.18	1.692E-01	5.088E-02	4.825E 06	-1.897E-07
354.0	1.3125	12000.	760.	2.00	0.001	0.14	1.125E-01	3.957E-02	1.249E 13	-4.433E-14

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	1.6250	7800.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.100E 00	-2.754E-01
354.0	1.6250	7800.	760.	0.50	0.003	0.14	2.538E-01	5.675E-02	4.863E 00	-1.510E-01
354.0	1.6250	7800.	760.	0.50	0.002	0.14	1.971E-01	5.675E-02	1.562E 01	-3.990E-02
354.0	1.6250	7800.	760.	0.50	0.001	0.12	1.125E-01	4.864E-02	3.343E 02	-1.286E-03
354.0	1.6250	7800.	760.	1.00	0.004	0.20	2.827E-01	8.107E-02	1.788E 01	-7.053E-02
354.0	1.6250	7800.	760.	1.00	0.003	0.22	2.538E-01	6.219E-02	5.515E 01	-2.033E-02
354.0	1.6250	7800.	760.	1.00	0.002	0.20	1.971E-01	5.653E-02	4.529E 02	-2.013E-03
354.0	1.6250	7800.	760.	1.00	0.001	0.16	1.125E-01	4.523E-02	1.633E 05	-3.564E-06
354.0	1.6250	7800.	760.	1.50	0.004	0.26	2.827E-01	7.349E-02	1.022E 02	-1.518E-02
354.0	1.6250	7800.	760.	1.50	0.003	0.24	2.538E-01	6.784E-02	4.973E 02	-2.639E-03
354.0	1.6250	7800.	760.	1.50	0.002	0.20	1.971E-01	5.653E-02	9.637E 03	-9.439E-05
354.0	1.6250	7800.	760.	1.50	0.001	0.16	1.125E-01	4.523E-02	6.602E 07	-8.818E-09
354.0	1.6250	7800.	760.	2.00	0.004	0.28	2.827E-01	7.915E-02	5.545E 02	-3.221E-03
354.0	1.6250	7800.	760.	2.00	0.003	0.24	2.538E-01	6.784E-02	3.940E 03	-3.325E-04
354.0	1.6250	7800.	760.	2.00	0.002	0.22	1.692E-01	6.219E-02	2.508E 05	-4.389E-06
354.0	1.6250	7800.	760.	2.00	0.001	0.16	1.125E-01	4.523E-02	2.668E 10	-2.182E-11
354.0	1.6250	12000.	760.	0.50	0.004	0.18	2.827E-01	7.296E-02	7.807E 00	-2.179E-01
354.0	1.6250	12000.	760.	0.50	0.003	0.18	2.120E-01	7.296E-02	1.962E 01	-7.966E-02
354.0	1.6250	12000.	760.	0.50	0.002	0.16	1.692E-01	6.485E-02	9.519E 01	-1.245E-02
354.0	1.6250	12000.	760.	0.50	0.001	0.12	1.125E-01	4.864E-02	7.643E 03	-8.628E-05
354.0	1.6250	12000.	760.	1.00	0.004	0.26	2.827E-01	7.349E-02	1.151E 02	-2.072E-02
354.0	1.6250	12000.	760.	1.00	0.003	0.24	2.538E-01	6.784E-02	5.831E 02	-3.462E-03
354.0	1.6250	12000.	760.	1.00	0.002	0.20	1.971E-01	5.653E-02	1.219E 04	-1.148E-04
354.0	1.6250	12000.	760.	1.00	0.001	0.16	1.125E-01	4.523E-02	1.048E 08	-8.549E-09
354.0	1.6250	12000.	760.	1.50	0.004	0.28	2.827E-01	7.915E-02	1.466E 03	-1.873E-03
354.0	1.6250	12000.	760.	1.50	0.003	0.26	2.120E-01	7.349E-02	1.653E 04	-1.431E-04
354.0	1.6250	12000.	760.	1.50	0.002	0.22	1.692E-01	6.219E-02	1.698E 06	-9.973E-07
354.0	1.6250	12000.	760.	1.50	0.001	0.16	1.125E-01	4.523E-02	1.072E 12	-8.353E-13
354.0	1.6250	12000.	760.	2.00	0.004	0.28	2.827E-01	7.915E-02	1.665E 04	-1.648E-04
354.0	1.6250	12000.	760.	2.00	0.003	0.26	2.120E-01	7.349E-02	4.211E 05	-5.617E-06
354.0	1.6250	12000.	760.	2.00	0.002	0.22	1.692E-01	6.219E-02	2.026E 08	-8.359E-09
354.0	1.6250	12000.	760.	2.00	0.001	0.15	1.125E-01	4.523E-02	1.097E 16	-8.161E-17

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	2.0000	7800.	760.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.100E 00	-3.388E-01
354.0	2.0000	7800.	760.	0.50	0.003	0.18	2.538E-01	7.296E-02	8.970E 00	-1.489E-01
354.0	2.0000	7800.	760.	0.50	0.002	0.16	1.971E-01	6.485E-02	3.008E 01	-3.225E-02
354.0	2.0000	7800.	760.	0.50	0.001	0.14	1.125E-01	5.675E-02	1.279E 03	-5.619E-04
354.0	2.0000	7800.	760.	1.00	0.004	0.24	2.827E-01	9.728E-02	3.914E 01	-5.532E-02
354.0	2.0000	7800.	760.	1.00	0.003	0.26	2.538E-01	7.349E-02	1.491E 02	-1.277E-02
354.0	2.0000	7800.	760.	1.00	0.002	0.22	2.249E-01	6.219E-02	1.666E 03	-8.138E-04
354.0	2.0000	7800.	760.	1.00	0.001	0.18	1.264E-01	5.088E-02	2.089E 06	-4.340E-07
354.0	2.0000	7800.	760.	1.50	0.004	0.30	2.827E-01	8.480E-02	3.012E 02	-8.390E-03
354.0	2.0000	7800.	760.	1.50	0.003	0.28	2.538E-01	7.915E-02	2.129E 03	-1.031E-03
354.0	2.0000	7800.	760.	1.50	0.002	0.24	1.971E-01	6.784E-02	8.417E 04	-1.915E-05
354.0	2.0000	7800.	760.	1.50	0.001	0.18	1.264E-01	5.088E-02	3.020E 09	-3.002E-10
354.0	2.0000	7800.	760.	2.00	0.004	0.30	2.827E-01	8.480E-02	2.019E 03	-1.248E-03
354.0	2.0000	7800.	760.	2.00	0.003	0.28	2.538E-01	7.915E-02	2.739E 04	-8.012E-05
354.0	2.0000	7800.	760.	2.00	0.002	0.24	1.971E-01	6.784E-02	3.689E 06	-4.370E-07
354.0	2.0000	7800.	760.	2.00	0.001	0.18	1.264E-01	5.088E-02	4.366E 12	-2.077E-13
354.0	2.0000	12000.	760.	0.50	0.004	0.22	2.827E-01	8.917E-02	1.463E 01	-2.002E-01
354.0	2.0000	12000.	760.	0.50	0.003	0.20	2.538E-01	8.107E-02	3.763E 01	-6.154E-02
354.0	2.0000	12000.	760.	0.50	0.002	0.22	2.249E-01	6.219E-02	3.007E 02	-6.954E-03
354.0	2.0000	12000.	760.	0.50	0.001	0.14	1.125E-01	5.675E-02	6.020E 04	-1.835E-05
354.0	2.0000	12000.	760.	1.00	0.004	0.30	2.827E-01	8.480E-02	3.487E 02	-1.115E-02
354.0	2.0000	12000.	760.	1.00	0.003	0.28	2.538E-01	7.915E-02	2.591E 03	-1.303E-03
354.0	2.0000	12000.	760.	1.00	0.002	0.24	1.971E-01	6.784E-02	1.126E 05	-2.203E-05
354.0	2.0000	12000.	760.	1.00	0.001	0.18	1.264E-01	5.088E-02	5.286E 09	-2.639E-10
354.0	2.0000	12000.	760.	1.50	0.004	0.30	2.827E-01	8.480E-02	6.511E 03	-5.953E-04
354.0	2.0000	12000.	760.	1.50	0.003	0.28	2.538E-01	7.915E-02	1.319E 05	-2.559E-05
354.0	2.0000	12000.	760.	1.50	0.002	0.24	1.971E-01	6.784E-02	3.777E 07	-6.566E-08
354.0	2.0000	12000.	760.	1.50	0.001	0.18	1.264E-01	5.088E-02	3.843E 14	-3.630E-15
354.0	2.0000	12000.	760.	2.00	0.004	0.30	2.827E-01	8.480E-02	1.216E 05	-3.187E-05
354.0	2.0000	12000.	760.	2.00	0.003	0.28	2.538E-01	7.915E-02	6.715E 06	-5.027E-07
354.0	2.0000	12000.	760.	2.00	0.002	0.24	1.971E-01	6.784E-02	1.267E 10	-1.957E-10
354.0	2.0000	12000.	760.	2.00	0.001	0.18	1.264E-01	5.088E-02	2.794E 19	-4.993E-20

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	1.3125	7800.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.094E 00	-4.192E 00
354.0	1.3125	7800.	860.	0.50	0.003	0.02	4.480E-02	4.000E-02	1.159E 00	-2.484E 00
354.0	1.3125	7800.	860.	0.50	0.002	0.12	1.692E-01	4.864E-02	7.730E 00	-9.077E-01
354.0	1.3125	7800.	860.	0.50	0.001	0.10	1.125E-01	4.053E-02	7.643E 01	-5.624E-02
354.0	1.3125	7800.	860.	1.00	0.004	0.16	2.827E-01	6.485E-02	7.641E 00	-1.635E 00
354.0	1.3125	7800.	860.	1.00	0.003	0.16	2.120E-01	6.485E-02	1.924E 01	-5.956E-01
354.0	1.3125	7800.	860.	1.00	0.002	0.14	1.692E-01	5.675E-02	6.952E 01	-9.394E-02
354.0	1.3125	7800.	860.	1.00	0.001	0.14	1.125E-01	3.957E-02	1.003E 04	-6.335E-04
354.0	1.3125	7800.	860.	1.50	0.004	0.22	2.827E-01	6.219E-02	3.161E 01	-5.125E-01
354.0	1.3125	7800.	860.	1.50	0.003	0.20	2.120E-01	5.653E-02	1.036E 02	-1.264E-01
354.0	1.3125	7800.	860.	1.50	0.002	0.18	1.692E-01	5.088E-02	1.156E 03	-9.073E-03
354.0	1.3125	7800.	860.	1.50	0.001	0.14	1.125E-01	3.957E-02	1.005E 06	-6.324E-06
354.0	1.3125	7800.	860.	2.00	0.004	0.20	1.712E-01	9.107E-02	1.025E 02	-1.564E-01
354.0	1.3125	7800.	860.	2.00	0.003	0.22	2.120E-01	6.219E-02	5.964E 02	-2.635E-02
354.0	1.3125	7800.	860.	2.00	0.002	0.18	1.692E-01	5.088E-02	1.213E 04	-8.658E-04
354.0	1.3125	7800.	860.	2.00	0.001	0.14	1.125E-01	3.957E-02	1.006E 08	-6.315E-08
354.0	1.3125	12000.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.148E 00	-4.091E 00
354.0	1.3125	12000.	860.	0.50	0.003	0.14	2.120E-01	5.675E-02	7.214E 00	-1.850E 00
354.0	1.3125	12000.	860.	0.50	0.002	0.14	1.692E-01	5.675E-02	3.173E 01	-4.163E-01
354.0	1.3125	12000.	860.	0.50	0.001	0.12	1.125E-01	3.392E-02	8.908E 02	-9.070E-03
354.0	1.3125	12000.	860.	1.00	0.004	0.22	2.827E-01	6.219E-02	3.454E 01	-7.196E-01
354.0	1.3125	12000.	860.	1.00	0.003	0.20	2.120E-01	5.653E-02	1.167E 02	-1.725E-01
354.0	1.3125	12000.	860.	1.00	0.002	0.18	1.692E-01	5.088E-02	1.385E 03	-1.167E-02
354.0	1.3125	12000.	860.	1.00	0.001	0.14	1.125E-01	3.957E-02	1.432E 06	-6.827E-06
354.0	1.3125	12000.	860.	1.50	0.004	0.20	1.712E-01	8.107E-02	2.255E 02	-1.163E-01
354.0	1.3125	12000.	860.	1.50	0.003	0.22	2.120E-01	6.219E-02	1.594E 03	-1.515E-02
354.0	1.3125	12000.	860.	1.50	0.002	0.18	1.692E-01	5.088E-02	5.155E 04	-3.134E-04
354.0	1.3125	12000.	860.	1.50	0.001	0.14	1.125E-01	3.957E-02	1.713E 09	-5.705E-09
354.0	1.3125	12000.	860.	2.00	0.004	0.22	1.712E-01	8.917E-02	1.764E 03	-1.792E-02
354.0	1.3125	12000.	860.	2.00	0.003	0.22	2.120E-01	6.219E-02	1.867E 04	-1.296E-03
354.0	1.3125	12000.	860.	2.00	0.002	0.18	1.692E-01	5.088E-02	1.919E 06	-8.422E-06
354.0	1.3125	12000.	860.	2.00	0.001	0.14	1.125E-01	3.957E-02	2.050E 12	-4.769E-12

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	1.6250	7800.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.094E 00	-5.186E 00
354.0	1.6250	7800.	860.	0.50	0.003	0.14	2.538E-01	5.675E-02	4.424E 00	-3.007E 00
354.0	1.6250	7800.	860.	0.50	0.002	0.14	1.971E-01	5.675E-02	1.325E 01	-8.406E-01
354.0	1.6250	7800.	860.	0.50	0.001	0.12	1.125E-01	4.864E-02	2.360E 02	-3.219E-02
354.0	1.6250	7800.	860.	1.00	0.004	0.20	2.827E-01	8.107E-02	1.504E 01	-1.496E 00
354.0	1.6250	7800.	860.	1.00	0.003	0.22	2.538E-01	6.219E-02	4.337E 01	-4.585E-01
354.0	1.6250	7800.	860.	1.00	0.002	0.20	1.971E-01	5.653E-02	3.139E 02	-5.130E-02
354.0	1.6250	7800.	860.	1.00	0.001	0.16	1.125E-01	4.523E-02	7.955E 04	-1.291E-04
354.0	1.6250	7800.	860.	1.50	0.004	0.26	2.827E-01	7.349E-02	7.747E 01	-3.548E-01
354.0	1.6250	7800.	860.	1.50	0.003	0.24	2.538E-01	6.784E-02	3.428E 02	-6.764E-02
354.0	1.6250	7800.	860.	1.50	0.002	0.20	1.971E-01	5.653E-02	5.561E 03	-2.887E-03
354.0	1.6250	7800.	860.	1.50	0.001	0.16	1.125E-01	4.523E-02	2.244E 07	-4.579E-07
354.0	1.6250	7800.	860.	2.00	0.004	0.26	2.827E-01	7.349E-02	3.303E 02	-8.239E-02
354.0	1.6250	7800.	860.	2.00	0.003	0.24	2.538E-01	6.784E-02	2.399E 03	-9.641E-03
354.0	1.6250	7800.	860.	2.00	0.002	0.20	1.971E-01	5.653E-02	9.853E 04	-1.629E-04
354.0	1.6250	7800.	860.	2.00	0.001	0.16	1.125E-01	4.523E-02	6.329E 09	-1.623E-09
354.0	1.6250	12000.	860.	0.50	0.004	0.18	2.827E-01	7.296E-02	6.902E 00	-4.436E 00
354.0	1.6250	12000.	860.	0.50	0.003	0.16	2.538E-01	6.485E-02	1.326E 01	-1.688E 00
354.0	1.6250	12000.	860.	0.50	0.002	0.16	1.692E-01	6.485E-02	7.244E 01	-2.896E-01
354.0	1.6250	12000.	860.	0.50	0.001	0.12	1.125E-01	4.864E-02	4.472E 03	-2.602E-0[illegible]
354.0	1.6250	12000.	860.	1.00	0.004	0.26	2.827E-01	7.349E-02	8.662E 01	-4.875E-01
354.0	1.6250	12000.	860.	1.00	0.003	0.24	2.538E-01	6.784E-02	3.981E 02	-8.956E-02
354.0	1.6250	12000.	860.	1.00	0.002	0.20	1.971E-01	5.653E-02	6.938E 03	-3.560E-03
354.0	1.6250	12000.	860.	1.00	0.001	0.16	1.125E-01	4.523E-02	3.463E 07	-4.564E-07
354.0	1.6250	12000.	860.	1.50	0.004	0.28	2.827E-01	7.915E-02	9.468E 02	-5.118E-02
354.0	1.6250	12000.	860.	1.50	0.003	0.24	2.538E-01	6.784E-02	7.943E 03	-4.478E-03
354.0	1.6250	12000.	860.	1.50	0.002	0.22	1.692E-01	6.219E-02	7.186E 05	-4.158E-05
354.0	1.6250	12000.	860.	1.50	0.001	0.16	1.125E-01	4.523E-02	2.038E 11	-7.755E-11
354.0	1.6250	12000.	860.	2.00	0.004	0.28	2.827E-01	7.915E-02	9.297E 03	-5.207E-03
354.0	1.6250	12000.	860.	2.00	0.003	0.26	2.120E-01	7.349E-02	1.938E 05	-2.154E-04
354.0	1.6250	12000.	860.	2.00	0.002	0.22	1.692E-01	6.219E-02	6.437E 07	-4.642E-07
354.0	1.6250	12000.	860.	2.00	0.001	0.16	1.125E-01	4.523E-02	1.199E 15	-1.318E-14

PUMP OPTIMUM

MOLE. WEIGHT	DIAMETER	SPEED	TEMP.	LENGTH	RADIAL CLEARANCE	GROVE WIDTH	LAND WIDTH	GROVE DEPTH	PRESSURE RATIO	LEAKAGE
354.0	2.0000	7800.	860.	0.50	0.004	0.02	5.973E-02	4.000E-02	1.094E 00	-6.379E 00
354.0	2.0000	7800.	860.	0.50	0.003	0.18	2.538E-01	7.296E-02	7.865E 00	-3.051E 00
354.0	2.0000	7800.	860.	0.50	0.002	0.16	1.971E-01	6.485E-02	2.453E 01	-7.034E-01
354.0	2.0000	7800.	860.	0.50	0.001	0.14	1.125E-01	5.675E-02	8.329E 02	-1.523E-02
354.0	2.0000	7800.	860.	1.00	0.004	0.26	3.384E-01	7.349E-02	2.833E 01	-1.222E 00
354.0	2.0000	7800.	860.	1.00	0.003	0.26	2.538E-01	7.349E-02	1.105E 02	-3.049E-01
354.0	2.0000	7800.	860.	1.00	0.002	0.22	2.249E-01	6.219E-02	1.068E 03	-2.241E-02
354.0	2.0000	7800.	860.	1.00	0.001	0.14	1.125E-01	5.675E-02	6.936E 05	-1.827E-05
354.0	2.0000	7800.	860.	1.50	0.004	0.30	2.827E-01	8.480E-02	2.139E 02	-2.088E-01
354.0	2.0000	7800.	860.	1.50	0.003	0.26	2.538E-01	7.349E-02	1.161E 03	-2.877E-02
354.0	2.0000	7800.	860.	1.50	0.002	0.24	1.971E-01	6.784E-02	4.265E 04	-6.670E-04
354.0	2.0000	7800.	860.	1.50	0.001	0.18	1.264E-01	5.088E-02	8.163E 08	-1.960E-08
354.0	2.0000	7800.	860.	2.00	0.004	0.30	2.827E-01	8.480E-02	1.280E 03	-3.477E-02
354.0	2.0000	7800.	860.	2.00	0.003	0.28	2.538E-01	7.915E-02	1.485E 04	-2.609E-03
354.0	2.0000	7800.	860.	2.00	0.002	0.24	1.971E-01	6.784E-02	1.490E 06	-1.909E-05
354.0	2.0000	7800.	860.	2.00	0.001	0.18	1.264E-01	5.088E-02	7.629E 11	-2.098E-11
354.0	2.0000	12000.	860.	0.50	0.004	0.20	3.384E-01	8.107E-02	1.048E 01	-4.197E 00
354.0	2.0000	12000.	860.	0.50	0.003	0.20	2.538E-01	8.107E-02	3.028E 01	-1.359E 00
354.0	2.0000	12000.	860.	0.50	0.002	0.18	1.971E-01	7.296E-02	1.877E 02	-1.724E-01
354.0	2.0000	12000.	860.	0.50	0.001	0.14	1.125E-01	5.675E-02	3.113E 04	-6.263E-04
354.0	2.0000	12000.	860.	1.00	0.004	0.30	2.827E-01	8.480E-02	2.455E 02	-2.797E-01
354.0	2.0000	12000.	860.	1.00	0.003	0.28	2.538E-01	7.915E-02	1.618E 03	-3.685E-02
354.0	2.0000	12000.	860.	1.00	0.002	0.24	1.971E-01	6.784E-02	5.606E 04	-7.808E-04
354.0	2.0000	12000.	860.	1.00	0.001	0.18	1.264E-01	5.088E-02	1.382E 09	-1.782E-08
354.0	2.0000	12000.	860.	1.50	0.004	0.30	2.827E-01	8.480E-02	3.846E 03	-1.779E-02
354.0	2.0000	12000.	860.	1.50	0.003	0.28	2.538E-01	7.915E-02	6.507E 04	-9.156E-04
354.0	2.0000	12000.	860.	1.50	0.002	0.24	1.971E-01	6.784E-02	1.327E 07	-3.297E-06
354.0	2.0000	12000.	860.	1.50	0.001	0.18	1.264E-01	5.088E-02	5.135E 13	-4.795E-13
354.0	2.0000	12000.	860.	2.00	0.004	0.30	2.827E-01	8.480E-02	6.027E 04	-1.135E-03
354.0	2.0000	12000.	860.	2.00	0.003	0.28	2.538E-01	7.915E-02	2.617E 06	-2.276E-05
354.0	2.0000	12000.	860.	2.00	0.002	0.24	1.971E-01	6.784E-02	3.143E 09	-1.393E-08
354.0	2.0000	12000.	860.	2.00	0.001	0.18	1.264E-01	5.088E-02	1.300E 18	-1.290E-17

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2. A. Guthrie and R. K. Wakerling, Vacuum Equipment and Techniques, McGraw-Hill Book Co., 1949.

3. L. Dunoyer, Vacuum Practice, Van Nostrand, New York, 1926.

APPENDIX B

TRANSITION FLOW THEORY OF THE MOLECULAR PUMP

Appendix A presents the theory of the molecular pump based on the assumption of purely molecular flow. The unique pressure ratio development, and hence flow restriction, of the molecular pump is dependent on the flow being in the molecular regime. If the flow, on the other hand, is in the continuum regime, the pressure ratio development of the pump is, for all practical purposes, nil. In between continuum flow and molecular flow lies a flow region called the transition regime. In this region the flow is a compromise between its two adjacent regions, the flow characteristics being weighted toward the region of greater proximity.

Within the molecular pump, there is always a transition occurring toward molecular flow as the flow passes from the high-pressure end to the low-pressure end. The degree to which molecular flow is achieved is dependent on the inlet conditions of the pump. If the flow is molecular entering the pump, the entire pumping process will be in molecular flow; this is the ideal operating condition for a molecular pump. On the other hand, if the inlet conditions are far enough into the continuum regime, the flow could remain in the continuum regime throughout the pump; essentially no pressure ratio development would occur. A third process occurs when the pump entrance flow is in the continuum regime, but not so far that molecular flow cannot be achieved within the pump. The sooner molecular flow is achieved, of course, the sooner the exponential pressure ratio development characteristic becomes predominant. This latter flow process is the type encountered in the SNAP-8 system. At the 300°F entrance condition, continuum flow is favored. The flow, however, is not too deeply into the continuum regime, and passes through the transition regime and somewhat into molecular flow.

The following discussion presents a mathematical model of the molecular pump which is applicable over the entire spectrum from continuum to molecular flow. As in Appendix A, the flow process is divided into three components: (1) flow down the helical channel due to the existing pressure gradient, (2) flow axially over the lands due to the pressure gradient, and (3) flow up the channel due to the effect of the rotor motion. The flow processes are now presented in the above order.

I. PRESSURE-INDUCED FLOW DOWN CHANNEL

Knudsen (Reference 1) proposed the following equation to define the flow of a fluid through a passageway:

$$Q = a' \, p + b' \, \frac{1 + c_1 \, p}{1 + c_2 \, p} \tag{1}$$

where

Q = volume flow at unit pressure

p = pressure

a', b', c_1, and c_2 = constants to be evaluated so as to make the flow applicable over the entire flow spectrum.

The evaluation of the constants in Equation (1) is the basic problem in deriving the molecular pump performance characteristics.

A. a' CONSTANT

By assuming purely continuum flow (i.e., p is very large) Equation (1) becomes

$$Q = a' \, p \tag{2}$$

which is seen to be the general form of ordinary Poisseuille flow. Reference 2 defines the flow of an incompressible fluid in a rectangular channel as

$$Q_1 = \frac{bh^3}{12\,\mu} \frac{dp}{d\ell} \left[1 - \frac{192}{\pi^5} \frac{h}{b} \left(\tanh \frac{\pi b}{2h} + \frac{1}{3^5} \tanh \frac{3\pi b}{2h} + \text{------} \right) \right] \tag{3}$$

or, to a close approximation,

$$Q_1 = \frac{bh^3}{12\,\mu} \frac{dp}{d\ell} \left[1 - 0.63 \frac{h}{b} \tanh \frac{\pi b}{2h} \right] \tag{4}$$

where

Q_1	= volume flow	p	= pressure
b	= groove width	ℓ	= length
h	= groove depth	μ	= viscosity

The weight flow rate for a compressible fluid is $W = Q_1 \frac{p}{RT}$ where R = gas constant and T = temperature. The volume flow at unit pressure, Q, is equal to WRT. Therefore, from Equation (4), the volume flow at unit pressure of a compressible fluid is

$$Q = \frac{bh^3}{12\,\mu}\left(1 - 0.63\,\frac{h}{b}\,\tanh\frac{\pi b}{2h}\right) p\,\frac{dp}{d\ell} \qquad (5)$$

Equation (5) is put into the context of the molecular pump by letting

$$d\ell = \frac{\pi D}{b + w}\,dL$$

where

D = diameter

w = land width

L = overall pump length

The final expression for continuum flow down the rectangular channel of the molecular pump becomes

$$Q = \frac{bh^3\,(b + w)\,K_3}{12\,\mu\,\pi D}\,p\,\frac{dp}{dL} \qquad (6)$$

where

$$K_3 = 1 - 0.63\,\frac{h}{b}\,\tanh\frac{\pi b}{2h}$$

Comparing Equations (2) and (6), the constant a' is given by

$$a' = \frac{bh^3\,(w + b)\,K_3}{12\,\mu\,\pi D}\,\frac{dp}{dL} \qquad (7)$$

B. b' CONSTANT

By assuming purely molecular flow (i.e., p is very small), Equation (1) becomes

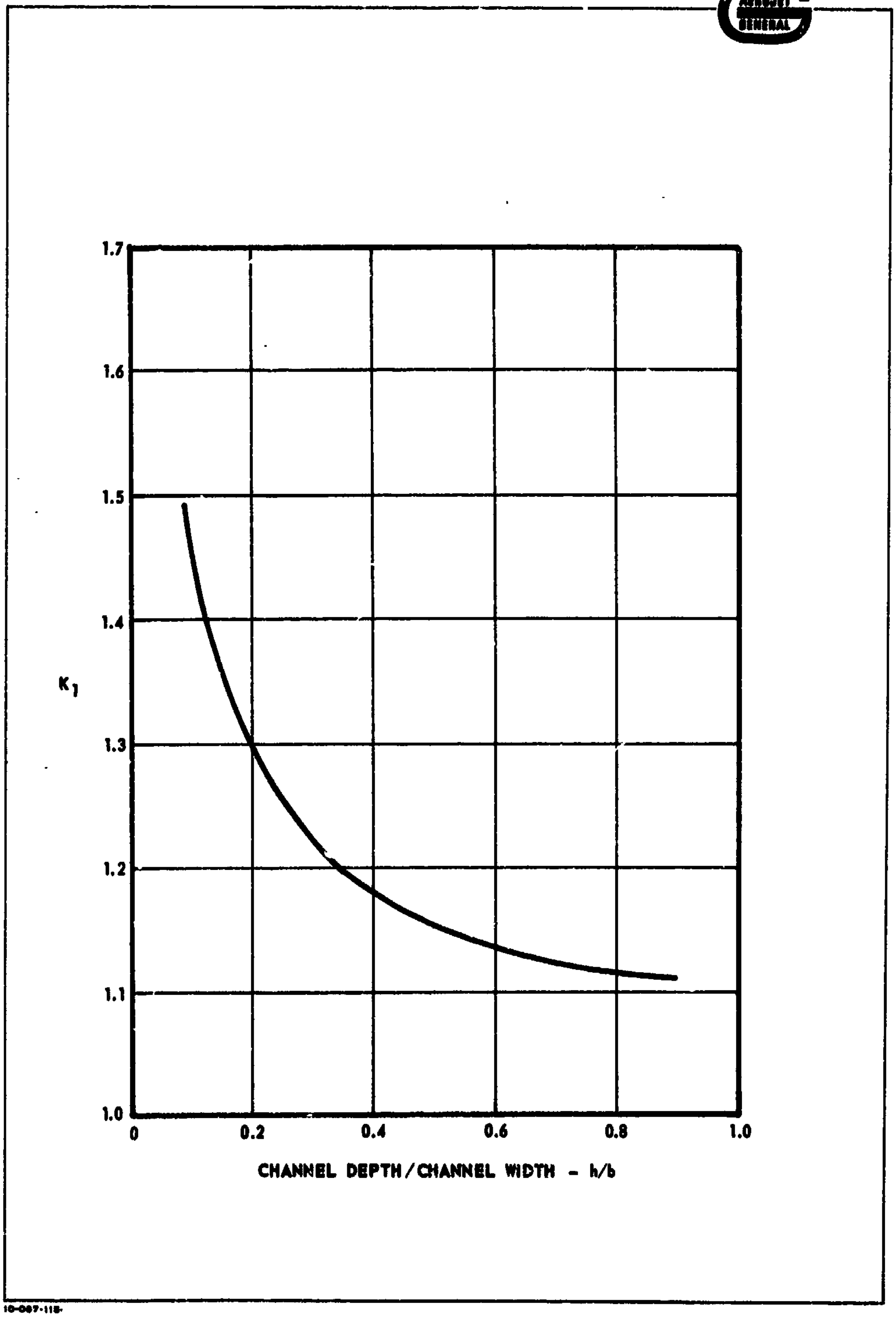
$$Q = b' \qquad (8)$$

From Equation (19) of Appendix A, b' is obtained as

$$b' = \frac{8\,K_1\,(w + b)\,(bh)^2}{3\,\pi D\,(h + b)}\,\sqrt{\frac{k\,T}{2\pi m}}\,\frac{dp}{dL} \qquad (9)$$

where

K_1 = geometrical factor given in Figure B-1



Geometrical Factor, K_1, for Long Rectangular Tube

Figure B-1

k = Boltzmann constant

m = mass of molecule

C. c_1/c_2 CONSTANT

Assume that the mean free path is small compared to the channel dimensions, but not negligibly small. With this assumption Equation (1) becomes

$$Q = a' \, p + \frac{c_1}{c_2} \, b' \qquad (10)$$

Substituting from Equations (7) and (9) for a' and b'

$$Q = \frac{bh^3 \, (w + b) \, K_3 \, p}{12 \, \mu \, \pi D} \, \frac{dp}{dL} + \frac{8 \, K_1 \, (w + b) \, (bh)^2}{3 \, \pi D \, (h + b)} \sqrt{\frac{k \, T}{2\pi m}} \, \frac{c_1}{c_2} \, \frac{dp}{dL} \, ,$$

or (11)

$$Q = \frac{(w + b) \, bh^3 \, K_3 \, p}{12 \, \mu \, \pi D} \, \frac{dp}{dL} \left[1 + \frac{32 \, K_1 \, \mu \, b}{K_3 h \, (h + b) \, p} \sqrt{\frac{k \, T}{2\pi m}} \, \frac{c_1}{c_2} \right]$$

But, in this flow regime, Poisseuille flow also holds provided a correction factor for slip at the boundaries is included. Therefore, the next step is to derive an expression for flow with slip in a rectangular channel.

It will be assumed that the flow can be approximated by flow between parallel, flat plates. In Figure B-2 therefore,

$$\frac{b}{h} \gg 1$$

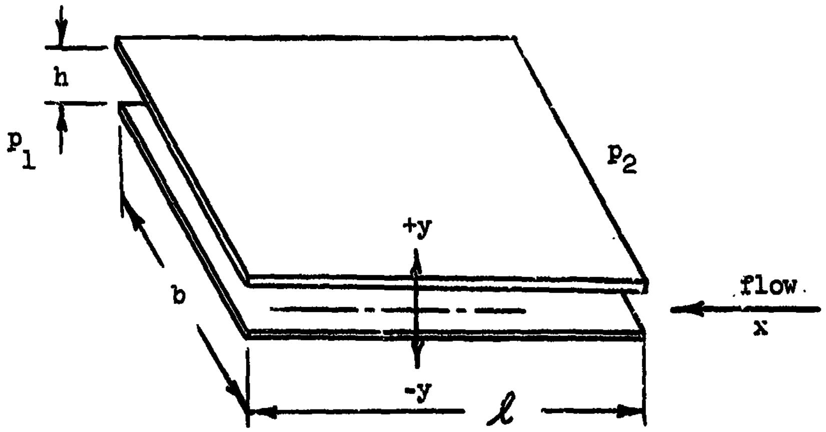


FIGURE B-2

Assume $v_o \neq 0$ (i.e., the fluid has a velocity at the plates).

Assume a frictional force exists at the plates given by

$$f = \epsilon \, S \, v_o \tag{12}$$

where

ϵ = numerical coefficient of force

S = area = $2b\ell$

For equilibrium at the plate surfaces,

$$2b \, \Delta y \, (p_1 - p_2) = f + 2b \, \ell \, \mu \, \frac{dv}{dy} \tag{13}$$

where

Δy = incremental thickness of fluid in y direction at wall

For small Δy, $2b \, \Delta y \, (p_1 - p_2) \longrightarrow 0$

Therefore,

$$-2b \, \ell \, \mu \, \frac{dv}{dy} = f = 2b \, \ell \, \epsilon \, v_o$$

or

$$v_o = - \frac{\mu}{\epsilon} \frac{dv}{dy} \tag{14}$$

The velocity profile for flow between flat plates can be derived from the following equation (Reference 3).

$$\frac{\partial^2 v}{\partial y^2} = - \frac{1}{\mu} \frac{\partial p}{\partial \ell} \tag{15}$$

Integrating,

$$\frac{\partial v}{\partial y} = - \frac{1}{\mu} \frac{\partial p}{\partial \ell} y + (\text{const})_1 \tag{16}$$

When $y = 0$, $\frac{\partial v}{\partial y} = 0$; therefore $(\text{const})_1 = 0$

From Equations (14) and (16) a new boundary condition which introduces slip is obtained as

$$v_o = \frac{\mu}{\epsilon} \frac{y}{\mu} \frac{dp}{d\ell} \tag{17}$$

Integrating Equation (16) and using the boundary condition from Equation (17) gives the velocity profile with slip as

$$v = \frac{1}{2\mu} \frac{dp}{d\ell} \left(\frac{h^2}{4} - y^2 + \frac{\mu h}{\epsilon} \right) \tag{18}$$

The volume flow is

$$V = 2b \int_0^{h/2} v \, dy$$

Substituting Equation (18) and integrating gives

$$V = \frac{bh^3}{12 \mu} \frac{dp}{d\ell} \left(1 + \frac{6 \mu}{h \epsilon} \right)$$

Denoting the "coefficient of slip" by $\zeta = \frac{\mu}{\epsilon}$

$$V = \frac{bh^3}{12 \mu} \frac{dp}{d\ell} \left(1 + \frac{6}{h} \zeta \right) \tag{19}$$

The flow can be put in terms of the molecular pump by substituting

$$Q = Vp$$

$$d\ell = \frac{\pi D}{b + w} dL$$

Therefore,

$$Q = \frac{bh^3 (b + w) K_3}{12 \mu \pi D} p \frac{dp}{dL} \left(1 + \frac{6}{h} \zeta \right) \tag{20}$$

Comparing Equations (11) and (20),

$$\frac{6}{h} \zeta = \frac{32 K_1 \mu b}{K_3 h (h + b) p} \sqrt{\frac{k T}{2\pi m}} \frac{c_1}{c_2}$$

$$\zeta = \frac{16 K_1 \mu b}{3K_3 (h + b) p} \sqrt{\frac{k T}{2\pi m}} \frac{c_1}{c_2} \tag{21}$$

By definition

$$\zeta = K \lambda \tag{22}$$

where

λ = mean free path

K = constant nearly equal to unity

The relationship between μ and λ is

$$\mu = \frac{1}{2} n m \bar{v} \lambda \tag{23}$$

where

n = molecules/unit volume

$\bar{v}$ = average velocity

Letting

$$\bar{v} = \left(\frac{8 k T}{\pi m} \right)^{1/2}$$

$$nm = \frac{p}{RTg}$$

$$\lambda = \frac{RTg \mu}{2 p \sqrt{\frac{k T}{2 \pi m}}} \tag{24}$$

Combining Equations (21), (22), and (24),

$$\frac{16 K_1 \mu b}{3 K_3 (h + b) p} \sqrt{\frac{k T}{2\pi m}} \frac{c_1}{c_2} = K \frac{RTg \mu}{2 p \sqrt{\frac{k T}{2\pi m}}}$$

and

$$\frac{c_1}{c_2} = K \frac{3\pi K_3 (h + b)}{16 K_1 b}$$

Knudsen found that for flow in tubes, $K = 0.85$ (Reference 1).

Assuming this value of $\mathcal{K}$,

$$\frac{c_1}{c_2} = \frac{K_3\ (h + b)}{2\ K_1\ b} \tag{25}$$

D. $c_2 - c_1$ CONSTANT

To evaluate $c_2 - c_1$, it is assumed that the mean free path is greater than the dimensions of the passageway, but not much greater. Now impacts with both the walls and with other molecules occur. The momentum of the moving molecules can then be carried to the walls by two processes: (1) by direct impact with the walls, and (2) by the molecules struck by these molecules. Knudsen (Reference 1) gives the following corrective factor to be applied to the basic equation for pure molecular flow.

$$\frac{1 + \frac{4A}{\lambda B} k_t}{1 + \frac{4A}{\lambda B}} \tag{26}$$

where

A = passageway cross-sectional area

B = perimeter of cross section

k_t is a constant introduced to account for the time elapsing between impacts of moving molecules and others, and transfer of this momentum to the walls. k_t has a value of approximately 1/2. Applying the correction factor to Equation (8) gives

$$Q = \frac{8\ K_1\ (w + b)\ (bh)^2}{3\ \pi D\ (h + b)} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{dp}{dL} \left[\frac{1 + \frac{4A}{\lambda B} k_t}{1 + \frac{4A}{\lambda B}} \right] \tag{27}$$

Assuming that $\frac{4A}{B} \ll \lambda$

$$Q = \frac{8\ K_1\ (w + b)\ (bh)^2}{3\ \pi D\ (h + b)} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{dp}{dL} \left[1 - (1 - k_t) \frac{4A}{\lambda B} \right]$$

Letting

$$A = bh$$

$$B = 2(b + h)$$

$$Q = \frac{8\ K_1\ (w + b)\ (bh)^2}{3\ \pi D\ (h + b)} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{dp}{dL} \left[1 - (1 - k_t) \frac{2bh}{\lambda(b + h)} \right] \tag{28}$$

For small values of p, Equation (1) becomes

$$Q = a' p + b' \left[1 - (c_2 - c_1) p\right] = b' \left[1 - \left|c_2 - c_1 - \frac{a'}{b'}\right| p\right]$$

Substituting for b' from Equation (9)

$$Q = \frac{8 K_1 (w + b) (bh)^2}{3 \pi D (h + b)} \sqrt{\frac{k T}{2\pi m}} \frac{dp}{dL} \left[1 - \left|c_2 - c_1 - \frac{a'}{b'}\right| p\right] \qquad (29)$$

Comparing Equations (28) and (29)

$$(1 - k_t) \frac{2 b h}{\lambda (b + h)} = p \left|c_2 - c_1 - \frac{a'}{b'}\right| \qquad (30a)$$

and

$$c_2 - c_1 = \frac{(1 - k_t) 2 b h}{\lambda (b + h) p} + \frac{a'}{b'} \qquad (30b)$$

From Equations (7) and (9),

$$\frac{a'}{b'} = \frac{K_3 h (h + b)}{32\mu K_1 b \sqrt{\frac{k T}{2\pi m}}} \qquad (31)$$

Substituting Equations (31) and (24) into (30) and letting $k_t = 1/2$ gives

$$c_2 - c_1 = \frac{h}{\mu \sqrt{\frac{k T}{2\pi m}}} \left(\frac{b}{\pi (b + h)} + \frac{K_3 (h + b)}{32 K_1 b} \right) \qquad (32)$$

Equations (25) and (32) when combined give c_1 and c_2 as

$$c_1 = \frac{\frac{K_3 (h + b) h}{2 K_1 b\mu \sqrt{\frac{k T}{2\pi m}}} \left(\frac{b}{\pi (b + h)} + \frac{K_3 (h + b)}{32 K_1 b} \right)}{1 - \frac{K_3 (h + b)}{2 K_1 b}} \qquad (33)$$

$$c_2 = \frac{\dfrac{h}{\mu\sqrt{\dfrac{k\,T}{2\pi m}}}\left(\dfrac{b}{\pi(b+h)} + \dfrac{K_3\,(h+b)}{32\,K_1\,b}\right)}{1 - \dfrac{K_3\,(h+b)}{2\,K_1\,b}} \tag{34}$$

The above expressions for c_1 and c_2 are only approximate and can be improved by the following process.

Let

$$c_2 = d\,H$$

$$c_1 = d\,J$$

where

d = constant to be evaluated

$$H = \frac{\dfrac{h}{\mu\sqrt{\dfrac{k\,T}{2\pi m}}}\left(\dfrac{b}{\pi(b+h)} + \dfrac{K_3\,(h+b)}{32\,K_1\,b}\right)}{1 - \dfrac{K_3\,(h+b)}{2\,K_1\,b}} \tag{35}$$

$$J = \frac{\dfrac{K_3\,(h+b)\,h}{2\,K_1\,b\,\mu\sqrt{\dfrac{k\,T}{2\pi m}}}\left(\dfrac{b}{\pi\,(b+h)} + \dfrac{K_3\,(h+b)}{32\,K_1\,b}\right)}{1 - \dfrac{K_3\,(h+b)}{2\,K_1\,b}} \tag{36}$$

From Equation (1),

$$Q = a'\,p + b'\,\frac{1 + d\,J\,p}{1 + d\,H\,p} \tag{37}$$

Differentiating Equation (37) with respect to p and setting the expression equal to zero gives the pressure at the minimum of the flow curve as

$$p_m = \frac{1}{dH}\left(\sqrt{\frac{b'\,d\,(H-J)}{a'}} - 1\right) \tag{38}$$

Knudsen found that at the minimum of the curve the product $p_m c_2$ is very nearly unity.

Therefore,

$$4 = d \frac{b'}{a'} (H - J)$$

and

$$d = \frac{4 a'}{b' (H - J)} \tag{39}$$

Combining with Equations (31), (35), and (36),

$$d = \frac{K_3 (b + h)}{8 K_1 b \left(\frac{b}{\pi (b + h)} + \frac{K_3 (h + b)}{32 K_1 b} \right)} \tag{40}$$

Combining Equations (35), (36), and (40),

$$c_2 = \frac{K_3 h (b + h)}{4 \mu \sqrt{\frac{k T}{2\pi m}} \left[2 K_1 b - K_3 (h + b) \right]} \tag{41}$$

$$c_1 = \frac{K_3^2 (b + h)^2 h}{8 K_1 b \mu \sqrt{\frac{k T}{2\pi m}} \left[2 K_1 b - K_3 (h + b) \right]} \tag{42}$$

The final expression for flow down a rectangular channel for any fluid state is found by combining Equations (1), (7), (9), (41), and (42).

$$Q = \frac{bh^3 (w + b) K_3 p}{12 \mu \pi D} \frac{dp}{dL}$$

$$+ \frac{8 K_1 (w + b)(bh)^2}{3 \pi D (h + b)} \sqrt{\frac{k T}{2\pi m}} \frac{dp}{dL} \left[\frac{1 + \dfrac{K_3^2 (b + h)^2 h}{8 K_1 b \mu \sqrt{\frac{k T}{2\pi m}} \left[2 K_1 b - K_3 (b + h) \right]} p}{1 + \dfrac{K_3 h (b + h)}{4 \mu \sqrt{\frac{k T}{2\pi m}} \left[2 K_1 b - K_3 (b + h) \right]} p} \right] \tag{43}$$

II. AXIAL LEAKAGE OVER LANDS

An equation of the form of Equation (1) is again used as indicated below.

$$Q = a'' \, p + b'' \, \frac{1 + c_3 \, p}{1 + c_4 \, p} \tag{44}$$

A. a" CONSTANT

By assuming purely continuum flow, Equation (44) becomes

$$Q = a'' \, p \tag{45}$$

The volume flow at unit pressure for Poisseuille flow is given by

$$Q = \frac{bh^3 \, p}{12 \, \mu} \, \frac{dp}{d\ell} \tag{46}$$

In terms of the molecular pump geometry,

$$b = \frac{\pi D}{\cos \phi} \quad \text{where } \phi = \text{helix angle}$$

$$h = \delta = \text{radial clearance}$$

$$\frac{dp}{d\ell} = \frac{w + b}{w} \cos \phi \, \frac{dp}{dL}$$

Inserting these expressions in Equation (46) gives the axial leakage for continuum flow as

$$Q = \frac{(\pi D) \, \delta^3 \, (w + b) \, p}{12 \mu w} \, \frac{dp}{dL} \tag{47}$$

Comparing Equations (45) and (47),

$$a'' = \frac{(\pi D) \, \delta^3 \, (w + b)}{12 \mu w} \, \frac{dp}{dL} \tag{48}$$

B. b" CONSTANT

By assuming purely molecular flow, Equation (44) becomes

$$Q = b'' \tag{49}$$

From Equation (23) of Appendix A, b" is obtained as

$$b'' = \frac{8\ K_2\ \delta^2\ (\pi D)\ (w + b)}{3w} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{dp}{dL} \tag{50}$$

where

K_2 = geometrical factor given in Figure B-3.

C. c_3/c_4 CONSTANT

Assume that the mean free path is small compared to the channel dimensions, but not negligibly small. Equation (44) becomes

$$Q = a''\ p + \frac{c_3}{c_4}\ b'' \tag{51}$$

Substituting from Equations (48) and (50),

$$Q = \frac{(\pi D)\ \delta^3\ (w + b)\ p}{12\mu w}\ \frac{dp}{dL} \left[1 + \frac{32\ K_2\ \mu}{\delta p} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{c_3}{c_4} \right] \tag{52}$$

But in this flow regime, Poisseuille flow with slip also holds. Equation (19), repeated below, gives the flow with slip for a rectangular passageway.

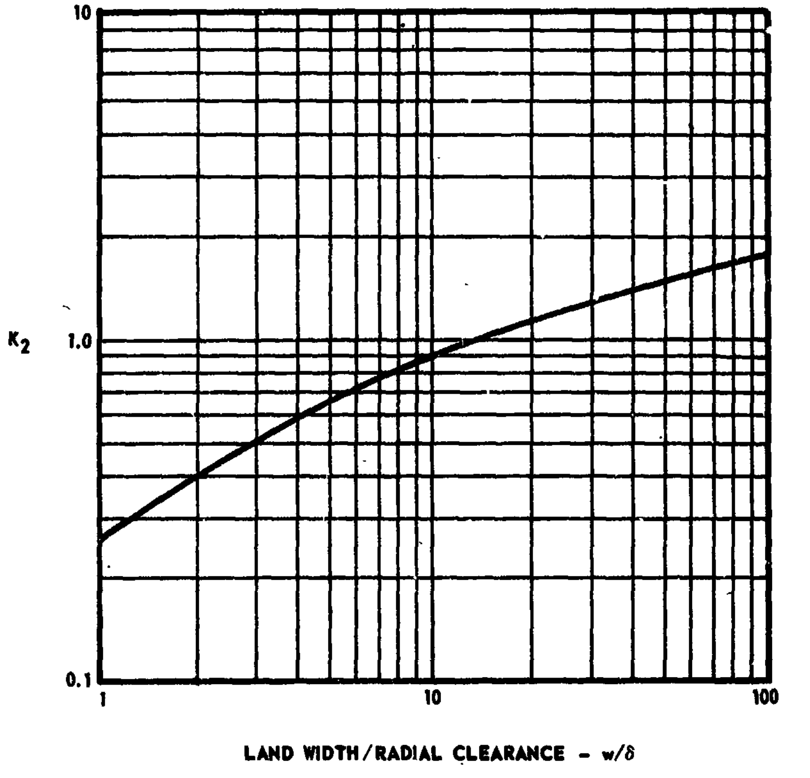
$$V = \frac{bh^3}{12\mu}\ \frac{dp}{d\ell} \left(1 + \frac{6}{h}\ \zeta \right)$$

Equation (19) is made applicable for flow over the lands by the following substitutions:

$$h = \delta$$

$$b = \frac{\pi D}{\cos \phi}$$

$$\frac{dp}{d\ell} = \frac{w + b}{w}\ \cos \phi\ \frac{dp}{dL}$$



Geometrical Factor, K_2, for Long Slit-Like Tube

Figure B-3

The flow at unit pressure becomes

$$Q = \frac{(\pi D)\ \delta^3\ (w + b)\ p}{12\mu w}\ \frac{dp}{dL}\ \left|1 + \frac{6}{\delta}\ \zeta\right| \tag{53}$$

Comparing Equations (52) and (53)

$$\frac{6}{\delta}\ \zeta = \frac{32\ K_2\ \mu}{\delta\ p}\ \sqrt{\frac{k\ T}{2\pi m}}\ \frac{c_3}{c_4}$$

$$\zeta = \frac{16\ K_2\ \mu}{3\ p}\ \sqrt{\frac{k\ T}{2\pi m}}\ \frac{c_3}{c_4} \tag{54}$$

From Equations (22), (24) and (54)

$$\frac{16\ K_2\ \mu}{3\ p}\ \sqrt{\frac{k\ T}{2\pi m}}\ \frac{c_3}{c_4} = K\ \frac{RTg\ \mu}{2\ p\ \sqrt{\frac{k\ T}{2\pi m}}}$$

$$\frac{c_3}{c_4} = K\ \frac{3\pi}{16\ K_2}$$

Letting K = 0.85, as found by Knudsen

$$\frac{c_3}{c_4} = \frac{1}{2\ K_2} \tag{55}$$

D. c_4-c_3 CONSTANT

Assume the mean free path is greater than the dimensions of the passageway, but not much greater. The corrective factor to be applied to the molecular flow equation is given by Equation (26) as

$$\frac{1 + \frac{4A}{\lambda B}\ k_t}{1 + \frac{4A}{\lambda B}}$$

Applying Equation (26) to Equation (50) gives the flow over the lands as

$$Q = \frac{8\ K_2\ \delta^2\ (\pi D)\ (w + b)}{3w} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{dp}{dL} \left[\frac{1 + \frac{4A}{\lambda B} k_t}{1 + \frac{4A}{\lambda B}} \right] \tag{56}$$

Assuming $\frac{4A}{B} \ll \lambda$,

$$Q = \frac{8\ K_2\ \delta^2\ (\pi D)\ (w + b)}{3w} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{dp}{dL} \left[1 - (1 - k_t)\ \frac{4A}{\lambda B} \right]$$

Letting $A = \frac{\pi D \delta}{\cos \phi}$

$B = \frac{2\pi D}{\cos \phi}$

$$Q = \frac{8\ K_2\ \delta^2\ (\pi D)\ (w + b)}{3w} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{dp}{dL} \left[1 - (1 - k_t)\ \frac{2\delta}{\lambda} \right] \tag{57}$$

For small pressures, Equation (44) becomes

$$Q = a''\ p + b'' \left[1 - (c_4 - c_3)\ p \right] = b'' \left[1 - (c_4 - c_3 - \frac{a''}{b''})\ p \right]$$

Substituting for b" from Equation (50),

$$Q = \frac{8\ K_2\ \delta^2\ (\pi D)\ (w + b)}{3w} \sqrt{\frac{k\ T}{2\pi m}}\ \frac{dp}{dL} \left[1 - (c_4 - c_3 - \frac{a''}{b''})\ p \right] \tag{58}$$

Comparing Equations (57) and (58)

$$c_4 - c_3 = \frac{(1 - k_t)\ 2\ \delta}{p\ \lambda} + \frac{a''}{b''} \tag{59}$$

From Equations (48) and (50),

$$\frac{a''}{b''} = \frac{\delta}{32\mu\ K_2 \sqrt{\frac{k\ T}{2\pi m}}} \tag{60}$$

Substituting Equations (24) and (60) into (59) and letting $k_t = 1/2$,

$$c_4 - c_3 = \frac{\delta}{\mu \sqrt{\frac{k\,T}{2\pi m}}} \left(\frac{1}{\pi} + \frac{1}{32\,K_2} \right) \tag{61}$$

Equations (55) and (61) together give

$$c_3 = \frac{\delta \left(\frac{1}{\pi} + \frac{1}{32\,K_2} \right)}{\mu (2\,K_2 - 1) \sqrt{\frac{k\,T}{2\pi m}}} \tag{62}$$

$$c_4 = \frac{2\,K_2\,\delta \left(\frac{1}{\pi} + \frac{1}{32\,K_2} \right)}{\mu (2\,K_2 - 1) \sqrt{\frac{k\,T}{2\pi m}}} \tag{63}$$

Again, an improvement can be made.

Let

$$c_4 = d\,H$$

$$c_3 = d\,J$$

where

$$H = \frac{2\,K_2\,\delta \left(\frac{1}{\pi} + \frac{1}{32\,K_2} \right)}{\mu (2\,K_2 - 1) \sqrt{\frac{k\,T}{2\pi m}}} \tag{64}$$

$$J = \frac{\delta \left(\frac{1}{\pi} + \frac{1}{32\,K_2} \right)}{\mu (2\,K_2 - 1) \sqrt{\frac{k\,T}{2\pi m}}} \tag{65}$$

From Equation (44),

$$Q = a''\,p + b''\,\frac{1 + d\,J\,p}{1 + d\,H\,p} \tag{66}$$

Differentiating with respect to p and solving for the pressure at the minimum of the flow curve gives

$$p_m = \frac{1}{dH}\left(\sqrt{\frac{b'' d (H - J)}{a''}} - 1\right) \tag{67}$$

Letting $p_m c_4$ = unity as found by Knudsen,

$$d = \frac{4a''}{b'' (H - J)} \tag{68}$$

Inserting expressions from Equations (60), (64), and (65),

$$d = \frac{1}{8 K_2 \left(\frac{1}{\pi} + \frac{1}{32 K_2}\right)} \tag{69}$$

Combining Equations (64), (65), and (69),

$$c_3 = \frac{\delta}{8 \mu K_2 \left(2 K_2 - 1\right)\sqrt{\frac{k T}{2\pi m}}} \tag{70}$$

$$c_4 = \frac{\delta}{4 \mu \left(2 K_2 - 1\right) \sqrt{\frac{k T}{2\pi m}}} \tag{71}$$

The final expression for flow over the lands for any fluid state is found by combining Equations (44), (48), (50), (70), and (71).

$$Q = \frac{(\pi D)\ \delta^3\ (w + b' p)}{12\mu w}\ \frac{dp}{dL}$$
$$+ \frac{8 K_2\ \delta^2\ (\pi D)\ (w + b)}{3w}\sqrt{\frac{k T}{2\pi m}}\ \frac{dp}{dL}\left[\frac{1 + \dfrac{\delta}{8 \mu K_2 (2 K_2 - 1)\sqrt{\frac{k T}{2\pi m}}}\, p}{1 + \dfrac{\delta}{4 \mu (2 K_2 - 1)\sqrt{\frac{k T}{2\pi m}}}\, p}\right] \tag{72}$$

III. ROTOR-INDUCED FLOW

The third and final flow process occurring within the molecular pump is the flow up the channel caused by the motion of the rotor. The rotor-induced flow for purely molecular flow is given by

$$Q = \frac{Nbh}{120\,(b + h)} \left[\frac{f_2\,(1 - f_1)\,(b + 2h) + f_2 b}{f_1 + f_2 - f_1 f_2} \right] \left[(\pi D)^2 - (w + b)^2 \right]^{1/2} p \qquad (73)$$

where

N = rotor speed, rpm

f = coefficient of momentum transfer

To a close approximation, the coefficient of momentum transfer equals unity which reduces Equation (73) to

$$Q = \frac{Nb^2 h}{120\,(h + b)} \left[(\pi D)^2 - (w + b)^2 \right]^{1/2} p \qquad (74)$$

Equation (74) is seen to be simply the cross-sectional area of the channel times one-half the velocity of the rotor in the direction of the channel times a modification factor to account for the relative area of stationary and moving members. Since the average fluid velocity between a moving and stationary surface is essentially one-half the velocity of the moving surface, regardless of whether the flow is in the molecular or continuum regime, Equation (74) becomes the applicable equation over the entire flow spectrum.

IV. NET FLOW

The net flow through the molecular pump is the rotor-induced flow minus the flow down the channel minus the flow over the lands. Combining Equations (43), (72), and (74), the net flow is

$$Q_N = Ap - \left(Bp + C\,\frac{1 + c_1 p}{1 + c_2 p} \right) \frac{dp}{dL} - \left(Dp + E\,\frac{1 + c_3 p}{1 + c_4 p} \right) \frac{dp}{dL} \qquad (75)$$

where

$$A = \frac{Nb^2 h}{120\,(h + b)} \left[(\pi D)^2 - (w + b)^2 \right]^{1/2} \qquad (76)$$

$$B = \frac{bh^3 (w + b) K_3}{12 \mu \pi D} \tag{77}$$

$$C = \frac{8 K_1 (w + b) (bh)^2}{3 \pi D (h + b)} \sqrt{\frac{k T}{2\pi m}} \tag{78}$$

$$D = \frac{(\pi D) \delta^3 (w + b)}{12 \mu w} \tag{79}$$

$$E = \frac{8 K_2 \delta^2 (\pi D) (w + b)}{3w} \sqrt{\frac{k T}{2\pi m}} \tag{80}$$

V. PRESSURE RATIO

The molecular pump develops its maximum pressure ratio when the net flow equals zero. Letting $Q_N = 0$ in Equation (75)

$$\frac{dp}{dL} = \frac{Ap}{C \dfrac{1 + c_1 p}{1 + c_2 p} + E \dfrac{1 + c_3 p}{1 + c_4 p} + (B + D) p} \tag{81}$$

Integrating,

$$\ln \left[p^{(C + E)} \left(1 + c_2 p\right)^{C \left(\frac{c_1}{c_2} - 1\right)} \left(1 + c_4 p\right)^{E \left(\frac{c_3}{c_4} - 1\right)} \right] + (B + D) p = AL + \text{CONST.}$$

Inserting the boundary conditions:

when $L = 0$, $p = p_{e_o}$

when $L = L$, $p = p_o$

$$\left[\left(\frac{p_o}{p_{e_o}}\right)^{(C + E)} \left(\frac{1 + c_2 p_o}{1 + c_2 p_{e_o}}\right)^{C \left(\frac{c_1}{c_2} - 1\right)} \left(\frac{1 + c_4 p_o}{1 + c_4 p_{e_o}}\right)^{E \left(\frac{c_3}{c_4} - 1\right)} \right] = e^{AL - (B+D) \left(p_o - p_{e_o}\right)} \tag{82}$$

where

A, B, C, D, E, c_1, c_2, c_3, c_4 are given by Equations (76), (77), (78), (79), (80) (41), (42), (70), (71).

Equation (82) defines the pressure ratio that the molecular pump can develop. The equation applies in molecular or continuum flow and accounts for any transition between flow states occurring within the pump itself. It is interesting to note that if pressures are assumed small in Equation (82) it reduces to the purely molecular flow case derived in Appendix A. Conversely, if pressures are assumed large, Equation (82) reduces to the equation of the screw, or visco-seal (Reference 4).

VI. LEAKAGE RATE

From Equation (75),

$$\frac{dp}{dL} = \frac{Ap - Q_N}{C\,\dfrac{1 + c_1\,p}{1 + c_2\,p} + E\,\dfrac{1 + c_3\,p}{1 + c_4\,p} + (B + D)\,p} \tag{83}$$

Integrating and using the boundary conditions

when $L = 0, \quad p = p_e$

when $L = L, \quad p = p_o$

$$\left(\frac{(c_2 p_o - H)\;(c_2 p_e + 1)}{(c_2 p_o + 1)\;(c_2 p_e - H)}\right)^F \left(\frac{(c_4 p_o - I)\;(c_4 p_e + 1)}{(c_4 p_o + 1)\;(c_4 p_e - I)}\right)^G \left(\frac{(A c_2 p_o{}^2 + M p_o - Q_N)}{(A c_2 p_e{}^2 + M p_e - Q_N)}\right)^J \left(\frac{(A c_4 p_o{}^2 + N p_o - Q_N)}{(A c_4 p_e{}^2 + N p_e - Q_N)}\right)^K =$$

$$\exp\left\{L - O\left[A\,(p_o - p_e) - Q_N\,\ell n\left(\frac{A\,p_e - Q_N}{A\,p_o - Q_N}\right)\right]\right\} \tag{84}$$

where

$$F = \frac{C\left[2\,Ac_2 - c_1\,(A - Q_N\,c_2)\right]}{2\,Ac_2\,(A + Q_N\,c_2)}$$

$$G = \frac{E\left[2\,Ac_4 - c_3\,(A - Q_N\,c_4)\right]}{2\,Ac_4\,(A + Q_N\,c_4)}$$

$$H = \frac{Q_N\,c_2}{A}$$

$$I = \frac{Q_N\,c_4}{A}$$

$$J = \frac{C\ c_1}{2\ A\ c_2}$$

$$K = \frac{E\ c_3}{2\ A\ c_4}$$

$$M = \left(A - Q_N\ c_2\right)$$

$$N = \left(A - Q_N\ c_4\right)$$

$$O = \frac{(B + D)}{A^2}$$

Equation (84) is the general solution for any pressures as boundary conditions. However, a considerable simplification of the equation is possible by letting $p_e = 0$, which is the actual operating condition when the molecular pump is used as a seal-to-space.

Letting $p_e = 0$, the leakage equation becomes

$$\left[\left(\frac{1 - \frac{A\ p_o}{Q_N}}{1 + c_2\ p_o} \right)^{\frac{C\left[2\ A\ c_2 - c_1\left(A - Q_N\ c_2\right)\right]}{2\ A\ c_2\left(A + Q_N\ c_2\right)}} \left(\frac{1 - \frac{A\ p_o}{Q_N}}{1 + c_4\ p_o} \right)^{\frac{E\left[2\ A\ c_4 - c_3\left(A - Q_N\ c_4\right)\right]}{2\ A\ c_4\left(A + Q_N\ c_4\right)}} \left(1 - \frac{A\ c_2\ p_o^2 + \left(A - Q_N\ c_2\right)\ p_o}{Q_N} \right)^{\frac{C\ c_1}{2\ A\ c_2}} \left(1 - \frac{A\ c_4\ p_o^2 + \left(A - Q_N\ c_4\right)\ p_o}{Q_N} \right)^{\frac{E\ c_3}{2\ A\ c_4}} \right] =$$

$$\exp\left\{ L - \frac{B + D}{A^2} \left[A\ p_o - Q_N\ \ln\left(\frac{Q_N}{Q_N - A\ p_o} \right) \right] \right\} \qquad (85)$$

where A, B, C, D, E, c_1, c_2, c_3, c_4 are given by Equations (76), (77), (78), (79), (80), (41), (42), (70), and (71). As with the pressure ratio equation, the leakage equation reduces to the equations for molecular flow and the visco-pump as the pressure becomes small and large, respectively.

For any given operating condition, there is an optimum geometry for the molecular pump defined by the variables b, w, and h. These variables can be optimized on the basis of maximum pressure ratio or minimum leakage, whichever is desired. The requirement for SNAP-8 is minimum leakage. The complexity of an optimization is apparent from the form of the pressure ratio and leakage equations. The complexity is increased due to the fact that neither pressure ratio nor leakage occur as explicit functions. Due to the probable variation of transition regime optimums from molecular regime optimums, an optimization program would be of considerable value for the SNAP-8 operating condition.

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SNAP-8 SEALS-TO-SPACE DEVELOPMENT TEST PROGRAM

Aerojet-General Corporation

ABSTRACT

The test program described in this report was conducted to determine the effectiveness of the molecular pump as a flow restrictor. The problems encountered and the remedial steps taken are outlined. Good correlation between theoretical predictions and test results is found. The correlation is particularly good when use is made of the transition flow theory which accounts for deviations from purely molecular flow. The molecular pump configuration selected for the SNAP-8 system shows good performance characteristics from both theoretical and experimental aspects. Appendixes contain two mathematical models of the molecular pump: one is based on molecular flow, and the other is an all-inclusive theory which covers operation over the entire range from molecular to continuum flow. Computer optimization results based on the molecular flow theory are included.